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A STUDY OF ROCKET EXHAUST PARTICLES

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ABSTRACT

The exhaust plumes generated by rocket motors are of significant military importance for missile detection, recognition and communication due to their electromagnetic emission and propagation properties. The plume is a high temperature, high velocity stream of gas and particles, into which the surrounding air is entrained. With improvements in the modelling of plume gas chemistry and turbulence, particles present in the plume have become more important in the computational prediction of the plume's flow field, and the subsequent prediction of plume emission and propagation characteristics.

This thesis describes research on plume particles, including the measurement of their physical characteristics and the addition of two phase coding (ie. particles) into current plume prediction software. Particle collections were carried out in plumes produced by rocket motors with double base and composite propellants (including aluminised). The collected particles were analysed to establish their chemical composition and size distribution. A laser Doppler anemometer system was successfully used to measure particle velocities in the plumes of 1.5kN double base motors. Particle tracking software was used to trace the paths of particles using a simplified prediction of the plume and it was found that the predicted particle behaviour was analogous to that measured experimentally.

Project management software was used during the research and its relevance was assessed in respect to the project's size and nature. The management of experimental trials was studied and a methodology formulated to help improve their future operation. The costs and benefits of the research were assessed and compared to other research projects. Many of the benefits gained, such as measurement techniques, require marketing to ensure that they are exploited in the future. Recommendations for future research are given that should enhance the present work.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATION

A_d	Particle projected area
AGARD	Advisory Group for Aerospace Research and Development
AIAA	American Institute of Aeronautics and Astronautics
BANDIR	Infrared emission band model
c	Speed of light
CCD	Charge Coupled Device
C_D	Coefficient of drag
CDB	Cast Double Base propellant
CFD	Computational Fluid Dynamics
CHAM	Concentration Heat And Momentum Ltd
COMPENDEX	Index of engineering and computing
d, D	Particle diameter
D_{10}, D(1,0)	Average particle diameter by number
D_{32}, D(3,2)	Average particle diameter by cross sectional area
D_{43}, D(4,3)	Average particle diameter by volume or mass
DERA	Defence Evaluation and Research Agency
DRIC	Defence Research Information Centre
DRA	Defence Research Agency
g	Gravitational acceleration
GENTRA	GENeral purpose particle TRacking Algorithm
IMechE	Institute of Mechanical Engineers
INSPEC	Database of Physical, Engineering and Computing information
IPSA	Inter-Phase Slip Algorithm
JANNAF	Joint Army Navy NASA Air Force
k-ϵ	Two equation turbulence model
k-w	Two equation turbulence model
LALLS	Low Angle Laser Light Scattering
LDA	Laser Doppler Anemometer
m_p	Mass of a particle
NACA	National Advisory Committee for Aeronautics

NASA	National Aeronautics and Space Administration
NTIS	National Technical Information Service
ONERA	Office National D'Etudes et de Recherches Aerospatiales
PERME	Propellants Explosives and Rocket Motor Establishment
PERT	Project Evaluation and Review Technique
PHOENICS	Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series
PIV	Particle Image Velocimetry
PMT	Photo Multiplier Tube
RARDE	Royal Armament Research and Development Establishment
Re	Reynolds number
REP	Rocket Exhaust Programme
S	Source or sink term
SEM	Scanning Electron Microscope
SIRRM	Standard InfraRed Radiation Model
U	Continuous phase velocity
UMIST	University of Manchester Institute of Science and Technology
v	Radial plume velocity
w	Axial plume velocity
X_p	Particle position
XRD	X-Ray Diffraction
α	Angle between particle movement and laser light
β	Angle between particle movement and observation direction
Γ	Exchange coefficient
θ	Incident angle in XRD
μ	Gas viscosity
μm	10^{-6} Meters
nm	10^{-9} Meters
ρ	Density
τ	Characteristic time
ϕ	Continuous phase property

1 INTRODUCTION

1.1 General background of the research

One of the main requirements for any missile is a means of propulsion and this is usually provided by a rocket motor. Only basic technologies are required to produce a simple rocket motor, in essence containing a combusting material inside a chamber and venting the resulting pressure to produce a thrust. A motor suitable for propelling a missile can be produced by refining the design of the motor and by introducing better materials for the propellant. As well as providing propulsion, rockets must be serviceable, safe and of reasonable cost. Their exhaust plumes may also have to exhibit certain emission and attenuation characteristics. The military environment is the most difficult for a missile to operate in, as opposing forces are endeavouring to disable it. To do so they must first of all detect the missile, track it, identify it as an adversary and then implement suitable countermeasures. Missile bodies are usually small, so it is usually easier to detect the exhaust plume. This may be by an active means, such as a radar signal, or passively by observing the infrared, visible or ultra-violet emissions. A communication link may be required to guide the missile to its destination, for example by radio waves. This link usually passes through the region behind the missile, so it must be ensured that the exhaust plume does not disrupt the communication, as control may be lost.

In order to produce effective missile systems it is therefore important to have information on the electromagnetic emissions of rocket exhaust plumes (termed its electromagnetic signature) and on how plumes attenuate communication links. Particles present in the plume have become significant contributors to plume emission and attenuation because of the reduction in other contributing factors, for example the lowering of plume temperatures by flame suppression. There is therefore a requirement for increasing the knowledge and understanding of exhaust plume particles.

1.2 Aims, objectives and methodology

The ultimate aims of plume science is to produce superior missile systems by;-

i) Reducing the electromagnetic signature of the rocket exhaust plume to a level that prevents its detection.
ii) Being able to accurately predict the electromagnetic signature of rocket propelled missiles.
iii) Being able to accurately predict and, if necessary, reduce the attenuation of electromagnetic radiation through a rocket exhaust plume.

The objective of this thesis is to contribute to the eventual achievement of the above aims by;-

i) Investigating the planning and management of the research work.
ii) Establishing techniques for the measurement of plume particle characteristics.
iii) Making measurements using the techniques in (ii) on specially seeded and "stock" rocket motors.
iv) Assessing current plume prediction computer programmes for the addition of two phase coding, using the information from (iii) for input values and validation.
v) Assess the research performed and make recommendations for future work.

The objectives were to be met by use of the following methodology;-

i) Literature review of previous work on rocket exhaust plumes.
ii) Experimentation on rocket motor plumes.
iii) Validation of the experimentation in (ii) using other flow fields, such as controllable high speed flows.
iv) Performing plume prediction with the existing programmes (ie. gas phase only, but with reaction chemistry).

v) Predicting particle trajectories in a simplified non reacting plume.

1.3 Outline of thesis

The remainder of this chapter identifies where rocket exhaust plume research is performed in the DRA, the UK and internationally. It also describes the background of the present investigation into plume particles and the international interest in the subject. Chapter 2 discusses the management and planning of the research programme and of experimental trials. This included the use of managerial software to aid in the planning and presentation of the project, and the formulation of a methodology for the effective management of experimental work. The costs and possible benefits of the work are discussed in Chapter 3, together with how the benefits could best be marketed. This gives an insight into the economic objectives behind the research and how it may best be exploited in the future.

In Chapter 4 the background technical reasons for studying plume science are discussed and the full implications of plume particles on the characteristics of rocket exhaust plumes defined. Rocket propellants and additives are reviewed in relation to their affect on performance and their contribution toward plume particles. The methods used to identify previous research are given, together with a review of relevant research work.

Methods suitable for the measurement of particle characteristics are discussed in Chapter 5, including those for determining particle size and composition, but excluding particle velocity measurement which is the subject of Chapter 6. Possible experimental methods are identified and the relative merits of intrusive rather than non-intrusive measurement techniques discussed. A description is then given of the experimental work required to develop two of these methods and the subsequent collection of plume particles from a number of different rocket motors. The selection of suitable analysis techniques is then described and the trends in measured particle characteristics discussed.

In Chapter 6 the possible techniques for performing plume particle velocity measurement are reviewed and the most suitable selected. The series of trials required to develop the system and obtain accurate measurements are then described.

Chapter 7 describes the use of computation fluid dynamic codes to predict exhaust plumes and the selection of a code with reaction rate chemistry capabilities for use in the present research. A description is then given of the prediction of particle trajectories through a simplified exhaust plume flow field (ie. non reacting). The trajectories are then evaluated against the experimental results and trends in particle behaviour discussed. Suggestions are then given for the future development of a two phase chemically reacting plume prediction code.

Although conclusions were drawn in the main body of the thesis, Chapter 8 highlights the important conclusions of the research. Overall recommendations are also given for future research which recognise the relative merits of the separate elements of the work.

1.4 Exhaust plume research in the Defence Research Agency

The DRA undertakes research and development in many different areas of military operation. Its constituent establishments are at Farnborough in Hampshire (formally the Royal Aircraft Establishment), Fort Halstead in Kent (formally the Royal Armament Research and Development Establishment), Malvern, in Worcestershire (formally Royal Signals Research Establishment) and a number of smaller sites. Although the section at Fort Halstead is the only one concentrating on the science of rocket exhaust plumes, other sections carry out plume research for their own applications. Examples are research into aircraft plumes at Farnborough and missile detection systems at Malvern.

The rocket plume research section at Fort Halstead originated at the Propellant Explosive and Rocket Motor Establishment at Westcott (Buckinghamshire, UK) and was transferred when that establishment became part of the Royal Ordnance. The section now leases sites at Westcott for taking measurements of static rocket motor firings and at present has plume measurement capabilities in the ultra-violet (spectral), visible (spectral and spatial), infrared (spectral and spatial) and radio frequencies. A computational predictive capability using two and three dimensional codes has been developed which incorporates a high level of expertise in combustion chemistry. Codes are also available to predict the plume's electromagnetic emission and signal attenuation using the plumes predicted by the flow field codes. Laboratory work is also carried out on plume combustion processes using gas burners.

1.5 Other exhaust plume researchers

The Royal Ordnance shares the DRA's objective of developing missile systems, but is also a major rocket motor manufacturer. By research into such areas as new propellants and nozzle geometries they aim to improve motor performance and thereby produce superior missile systems. Improvements may take the form of increased specific impulse, higher thrust, improved propellant handling characteristics, or reduced electromagnetic signature. Their experimental programme involves the firing of rocket motors at Westcott and Summerfield (Birmingham, UK). British Aerospace, who now own Royal Ordnance, also research plume phenomena to aid in the design of missile and aircraft systems. Most other researchers tend to be involved in more specific areas, such as developing homing heads or detection systems. Their interest stems from one specific project and is often sporadic.

Worldwide there are many more researchers interested in exhaust plumes. While performing literature searches some countries were predominant. The USA has probably the greatest research capability and their Government has funded research in a number of universities, as well as at their own civil and military establishments. The French have always been active in missile design, and have recently shown an increased interest in exhaust plume prediction. They have also carried out research in support of their space programme. Most other European countries have some interest in missile research, such as Germany, Italy and Spain. Russia, Japan, and Canada are also notable researchers.

1.6 Exhaust plume particle research

Previously only limited research on exhaust plume particles had been undertaken by the DRA. Development of a two phase code had previously been attempted, but little experimental data was available to validate it. In 1991 it was decided that a research programme on particles was required to address this deficiency in the plume prediction codes being developed. The effect of particles on plume prediction has become more significant with improvements in the modelling of other flow phenomena, for example the use of more powerful numerical methods and more refined plume chemistry. Particles are also important because they may interfere with missile communication and contribute towards the observable electromagnetic signature of the plume. They must therefore be included in any accurate prediction of the flow field or its electromagnetic phenomena.

Within the UK the amount of research directly related to plume particles seems to have been very small. Research has been carried out in other areas involving particles, such as filtration systems, coal dust combustion and particle velocity measurements techniques. Some attempts at collecting exhaust plume particles had also been made. A symposium was held in 1988 on the subject (RARDE 1988). The main finding was that there were many proposals for research, but little previous work. The level of interest seemed to be very high both in the requirement for information about plume particles and in the application of techniques to the plume environment (both computational and experimental).

Interest in particles is not limited to the UK. Most countries carrying out missile research seem to have a similar level of activity. They show an interest in plume particles, but have not developed a comprehensive research capability. The French have collected plume particles and measured particle diameter by laser diffraction. In the

USA the booster motors on the Space Shuttle were solid propellant (aluminised composite) and produced large quantities of particles. This inspired a great deal of research, such as the effect of the ejected particles on the environment. The USA military has also funded research on plume particles, including how particles effect a missile's electromagnetic signature.

2 MANAGEMENT OF THE RESEARCH PROGRAMME

2.1 Projects requiring management

Many types of project require management, whether they be a large complex tasks such as building an oil rig, or an apparently simple ones such as making a cup of tea. How the project is managed will depend on its importance, the aim of the project, its size and the nature of the project itself. For example, making a cup of tea normally requires no formal planning. A cup of tea prepared for a Royal visit would, however, merit a much higher level of planning and management to guarantee a first class product at the required time, while other factors would also need to be considered, such as security. It is important to recognise early on in a project what the principal objectives are and the nature and scope of the work to be carried out, including any constraints. The planning methods can then be established and implemented in an appropriate manner. In this section the areas of the PhD that required managing are outlined, with some initial thoughts on the management aims. Later on in the chapter the methods used and their outcome are discussed.

The PhD was a project with a set time scale, at the end of which enough information needed to have been gained to enable valid conclusions to be drawn. This information was gathered from literature, experimentation, computations and discussion. All these required planning to some degree to ensure the best results, for example research was more effective if the problem had been properly defined at the outset. The time scale also limited the research, as experimentation etc should produce results worthy of publication within three years, instead of for example five years, which might have been more appropriate. The aim seemed clear; to carry out effective research, in an appropriate order, producing suitable results and conclusions in the time scale allowed, and within any other constraints imposed, such as cost and resource availability.

One of the main ways of obtaining information was by experimentation. In this case the firing of rocket motors was the base for most experiments, with additional supporting data obtained by using a high speed flow rig at Cranfield. The expense involved in such experiments was very high due to the cost of the motors, typically £2000 each, plus the use of sites, manpower and equipment. Rocket firing trials often involved a number of people simultaneously trying to obtain measurements on a small number of motors, so forward planning and good communication were both very important in obtaining good results. The logistics of transporting and coordinating the availability of the equipment and its operators had to be considered, as well as the setting up the equipment and the coordination of the measurements during the few seconds of the firing. It was very important that everyone on a trial was confident that they knew what was going on and that they knew when a firing was due. Coordinating the preparation of several pieces of equipment at different locations could also prove difficult.

As well as the more physical aspects of research, such as trials work described above, other areas that needed managing included; reviewing previous work in the area (ie. literature searches, attending conferences etc), computational predictions and the writing of the thesis itself. In general these could be fitted around experimentation etc, as they were often carried out in small segments. This could have, however, lead to their neglect and the work may have been more coherent had larger blocks of time been allocated. Predictions were sometimes required prior to experimentation, so that velocities etc could be judged and optimal measurements made. They also played an important part in the design of equipment. Conversely intelligent prediction might only be made once some experimental results were available. The writing of the thesis is also worth mention because of the amount of effort that was expended in its production and the benefit of planning on the coherency of the finished product.

2.2 Variables and constraints

Some variables are common to most areas of planning and have well established methods for their control, for example budgeting expenditure or time. Variables may have constraints imposed upon them, such as a limited budget, or more individual ones, such as someone's availability. When starting on a project all the variables that may effect the outcome must be considered, together with any dependencies and constraints. In some situations the cost of a project is not important, for example motor racing, and it is the timescale and performance that matter. Conversely in other research the expenditure may be the limiting factor. The relationship between variables is also very import. For example, in the case of a racing car increasing the time scale to reduce the manning costs or to allow further development may mean that the final product has been superseded by the time it reaches the track and is therefore of no value.

During the PhD the variables which have proved to be important were;- time, cost or expenditure, equipment and expertise. The first two are the most commonly managed variables, although, as will be discussed below, the way in which they effected the current research was not as usually assumed. They were both important as they were required in all areas of the research and were of limited availability. The second two may be made up of the other two variables, ie. both time and expenditure are required to gain expertise or purchase equipment, but when planning the research it was the availability of these assets that was considered. Quality was another variable encountered and was a measure of the productivity of the other variables and of the standard of the resulting information.

Time is obviously important during any piece of research and with the time scale imposed during the PhD even more so. When considering time spent on the project it can be split into the author's time and other people's time. It also had to be divided up so that at the end of the PhD period sufficient work had been carried out in all areas of the research programme. The productivity when working was also very important, as often by combining tasks in a logical or more appropriate order more could be achieved. Time spent on work outside the PhD had also to be minimised, without affecting its quality. Other people also contributed their time to the work and had to make their time available. If their other work was of a higher priority their availability had to be accounted for during planning.

When ordering equipment time was also very important. In the case of the Centriseps (centrifugal separators used for particle collection) they were manufactured in batches for specific customers. The unit cost was considerably reduced by waiting until another customer had ordered a large consignment. However, this did mean conforming to other peoples timescales and ordering well ahead of a planned firing. Other peoples productivity was also very important, since what may have been a small task to the researcher may have taken much longer for someone else. Conversely by employing someone with the required expertise a task may have been more quickly carried out at a lower cost, or one that balanced the reduced time spent on it. Peoples reliability was also important, as if planning was based around a vital task which was allocated to someone unreliable, allowance had to be made for its late completion and effort made to prevent it affecting other tasks or people.

The expenditure on a project may often be the limiting factor in research, as it is this that pays for the time spent on it. In this case funding had been made available for the author's salary. In general any expenditure on the research was at the cost of other research being carried out within the author's section. This meant that as well as weighing up the relative merits of expenditure within the project some consideration had to be given to how it might effect other projects, ie. although funding was available a strong case was required before expenditure was justified. As funding was shared the best use was made of the resources by coordinating firings etc so that other experimenters could make use of them and in this way the cost could be shared. As mentioned above, by timing the ordering of equipment to fit in with large batches, expenditure was reduced by long term consideration of the future trials.

Because of the nature of the research specialised equipment was required to make measurements. This was principally the laser velocimetry system and particle collection equipment. In both cases suitable equipment had to be identified before the experimentation could continue. If they had proved to be unobtainable the research would have been severely hampered. In the case of the anemometer (used for the plume particle velocity measurement) once a suitable system had been chosen it was found that it could be borrowed from within the DRA, but expertise needed to be contracted in to operate it. The availability of the system had to be allowed for, as if it was required elsewhere there may have been a delay to the planned work. The particle collection equipment was either made from fairly rare material, ie. porous sintered stainless steel manufactured in small quantities in the USA, or in the case of the Centriseps their purchase had to be fitted around other peoples orders. In either case an error in the timing of ordering may have meant the delay of trials due to the lack of equipment.

To conclude, the significant variables were:- time - as a deadline and in its allocation, cost - in budgeting expenditure, equipment - in finding the correct type and ensuring its availability and expertise - in having experienced operators for equipment and having relevant knowledge to make correct decisions. There was therefore a requirement for a formal approach to planning and management.

2.3 Management of the PhD - initial

Before the PhD had started the envisaged work had been discussed with Prof Elder and Dr Tan, as well as inside the DRA. For the previous year the author had been doing limited research on rocket exhaust particles, so was aware of the problems involved. The Plume Science section was in the process of preparing a submission for funding for plume particle research from the DRA's Strategic Research Programme. At the initial PhD meeting a presentation on the background of the work was given. This started with general information on rocket exhaust plumes and why they required study. It then went onto discuss the particle content of the plume in more detail, describing the physical characteristics that required measurement and the various techniques that might be employed. The proposal prepared for the Strategic Research Programme was also supplied. This stated what the section was hoping to achieve with the research and the military reasons behind the work. The meeting then discussed the proposed work and how the objectives of the DRA and PhD could be combined. The result of this discussion was that a basic research plan had been outlined, although it was noted that because of the novelty of the proposed work its timescale and direction might change considerably during the period of the research. It was at this point that there was the first formal mention of a management scheme for the PhD. The proposed plan required illustrating to the panel, so that they could appreciate the timescales and durations of each part of the PhD.

On leaving the meeting the basic plan had been decided upon, but had not been fully documented. It was decided that the clearest way of doing this was graphically. A previously used presentation package called Harvard Graphics was chosen. This allowed the drawing of lines, shapes etc, together with text. It was soon found that adequate text to describe each part of the programme could not easily be included on the diagram. On printing out the plan the three year duration covered at least two sheets of A4 paper, even with little detail. With these limitation it was decided that a simplified plan would be presented (Figure 2.1). The vertical axis was labelled with the various areas of planned work and the horizontal axis marked with the months. Lines were then drawn to represent time periods and key dates when certain elements of work were being carried out and letters/numbers to represent actual events, such as the delivery of motors, or firings. To make sense of this it was supplied with a written description of each work area, which described each individual task.

At the next meeting there was a consensus that the timetable adequately indicated the work that was envisaged, although work not connected with the PhD had not been separated out (such as trials to obtain infrared signatures for other projects). It was decided that a revised timetable should be present at future meetings, with an indication of how the work was progressing in relation to the original plan. The nature of the tasks and milestones mentioned on the timetable were discussed. For example, some tasks, such as the delivery of motors, rely heavily on other tasks, ie. ordering the motors and that there may be a time delay between the two tasks that must be allowed for in planning. Some tasks were also much more important than others and had to be carefully monitored to assure progress.

A management course at Cranfield University was attended during this period, so the author's awareness of project planning increased, ie. the use of Gantt and PERT charts. The timetable previously produced was in essence a simplified Gantt chart (as in Figure 2.4), displaying the work load against time. This should then hopefully have shown up whenever there was a period of overload, such as when too many items were being carried out at the same time, or periods of under usage. By appreciating this the work load could then be more appropriately distributed. In this case the author's time was considered to be the key resource that needed planning, although other resources such as laboratory space or expenditure were also important.

A PERT chart helps to illustrate which parts of a project are more critical than others, ie. which ones determine the duration of the project and which ones that have to be carried out before others can start or finish (as in Figure 2.5). Tasks that determine the length of a project are said to make up the critical path. Although a PERT chart for the whole programme was not drawn, mainly because of its complexity, the principles that it involves were appreciated. For example the possible critical paths through the programme were identified. These being the collection of particles and their analysis, the measurement of particle velocities in the plume and computational predictions. Which one would actually become the critical path could not be judged because of the unknown nature of the work that they might require for completion. However, now that they had been identified as being the possible critical paths, work could be planned around them to ensure that they would not delay the completion.

For the next panel meeting in July 1993 a revised copy of the timetable was produced. This was in the same form as the previous one, with the lines and letters representing tasks moved to updated positions. A line was also added to represent the present date. At the meeting it was noted that various parts of the work had slipped slightly or been rearranged, but this could only be done in reference to the previous timetable. Because of the relatively small scale of the timetable this was not easy and again there was only limited information displayed about each task. There was also no idea of cost on the timetable, which might help in managing the programme. Changes to the timetable had also been time consuming to achieve, as every change involved correctly repositioning the line or indicating letter. Adding any more tasks would have proved very difficult, resulting in either a timetable covering further pages, or an even smaller scale. It was questioned if the time that was spent in preparation was worthwhile and whether other methods could be used to speed up the process or reap greater benefits.

Other graphics packages were suggested, but none seemed to offer any advantage over the one previously used, although the clarity and the time spent in preparation might have improved. At this point the use of commercial management packages was proposed. It was agreed that a suitable package may be available to help in the management of the PhD and a visit to the Cranfield school of management was arranged to test an example.

2.4 Management of the PhD - managerial software

As mentioned in the previous section it had become apparent that managerial software may have helped in the management and presentation of the research programme. The reasons why the manual methods of presentation had not proved satisfactory and the possible advantages of a management software approach were identified as follows;-

i) The timetable's time axis was inadequate.
ii) Extra tasks could not easily be added.
iii) Information supplied about each task was inadequate.
iv) Changes to the timetable had to be made by 'hand'.
v) Slippages etc were not apparent unless comparison with the previous timetable was made.
vi) Over allocation of resources were not identified.
vii) There was no control of the expenditure.
viii) Software can produce PERT and Gantt charts from the same information.
ix) Critical paths were not clearly identified.
x) The time spent in preparation must be in proportion to the benefits reaped.

With these thoughts in mind a meeting was held at Cranfield to discuss possible software. A list of commercially available management software was examined. After discussing the points above (the main ones being ease of use and clear presentation) suitable packages available at Cranfield were identified. These were Project Manager Workbench and Pertmaster, which were both tested by inputting simple projects and examining the various types of output available. It soon became apparent that Pertmaster was the most easy to operate and produced clear Gantt and PERT charts (Figures 2.2 and 2.3).

An article surveying the features of project management packages was also located (Claypole 1993). This information was very useful in determining the specific capabilities of different packages and Pertmaster compared well with the other packages, the only limitation noted being a maximum of 16,000 tasks, although this was not relevant to the research programme. Prices were also given, Pertmaster retailing at £1250. Packages at much lower prices appeared to have fewer functions available, so might be a false economy. From this information together with the previous experience of using Pertmaster it was decided to request a purchase of a copy. The case for purchase was helped by the possible future application of the software to other management problems within the section.

After this process of identifying a suitable package it was found that there was a DRA policy to use Micro Planner Professional. The author had been unaware of this and it was only as the order was passed to higher levels of management for approval that it was noted upon. The previously mentioned article (Claypole 1993) showed the main difference between the packages was that Pertmaster was more flexible in the way that it handled resources and multiple projects. Pertmaster was also slightly cheaper, but as the DRA buys software in bulk the prices stated are probably misleading. The copy received had been previously purchased, so that no further expense was incurred.

The software had not been received by the time of the next panel meeting and it was considered a retrograde step to produce another 'hand produced' timetable. An oral presentation was sufficient, as the work programme had not significantly altered. On using Micro Planner it soon became apparent that it was more complicated to use than Pertmaster; requiring a good knowledge of its basics before reliable results could be produced. Instruction manuals were also shared and were available for only a short period.

Micro Planner (Professional) worked by presenting the operator with menus of around eight choices. Selections were then made from the presented menus, resulting in the required action. This was probably one of the main disadvantage of the software, as moving between operations often meant spending time passing through a number of menus. Having set up the printer and screen, entering in the project began. The first decision was whether to split the work up into sub-projects. This meant that as well as the main project, which may have contained common or major tasks, separate sub-projects could be considered, for example the running of a trial. Information was then fed from the sub-project back to the main project, for example the trial completion date. In this way the main project plan could be kept simple, with detail hidden in the sub-projects. In the 'project' menu the basic structure of the project was outlined. This included deciding on a calender, working hours, what resources were available (people and equipment), assignment of cost codes and other methods of expenditure control. The items of work which made up the research were then defined as a number on tasks of varying length. Once the basic tasks were entered the relationships between them could be added. These were termed 'links' and joined tasks in various ways, such as that a task could only start once another one had finished. If definite dates were known for tasks they could be added, eg. a meeting, or a course. By the end of this stage all the relevant information about the prospective project had been entered.

Analysis was then performed via a set of menu options and could be dependent on time, cost or resources. After the analysis the software arranged the project into its predicted form and also highlighted any errors in the plan, eg. dates that could not be met or the over use of a resource. These could then be altered to allow the project to continue. Gantt and PERT charts of the project were produced on the screen and on paper. By examining these the efficiency of the plan could be seen, for example if there were long spells of inactivity. The tasks or resources used could then be changed to make the plan run more smoothly. As work proceeded the status of the tasks were entered on the plan, ie. their actual completion dates. If they were not completed on schedule, or removed from the plan, these changes were added. Subsequent analysis then indicated how the work compared with the plan, ie. delays and overruns etc. The plan was then altered to improve its efficiency etc. In this way the software helped the plan to grow and change as time passed and hopefully highlighted to the planner where improvements could have been made and could be made in the future.

Micro Planner charts were presented to the panel meeting in February 1994 and consisted of Gantt and PERT charts of the research carried out during the period of the PhD and a PERT chart of one trial (Figures 2.4. 2.5 and 2.6). The scale of the Gantt chart had to be limited to days rather than hours, otherwise the chart would have grown even larger. The charts keys show the symbols used for each type of task etc and how they are linked. The operation of the software was described to the panel members and how such things as critical paths could be easily found. At this point it was hoped that Gantt charts of the research programme would be presented at future meetings so that the panel members could judge the progress.

2.5 Management of the PhD - final method and critique

As the next panel meeting approached it became apparent that there was not enough time available to produce a fully revised Gantt chart of the programme and that available time would be more profitably spent on the tasks themselves, so a simple written outline of the future work presented to the panel instead. It was also found that the charts produced by the software were growing much too large. Often ten A4 pages or more were required for the Gantt chart of the project. This meant that the information was difficult interpret because of the sheer size of the output. Scaling this down did not seem possible in the software and reduction by photocopying involved having to paste together the various fragments. At the meeting the large Gantt chart previously presented was not missed and the general consensus was that the time spent on preparing the chart was not justified.

In subsequent meetings the research had reached a stage where the future work was clearly understood by the panel members, so instead of having to present them with a written report an oral description of the progress of the work sufficed. In the last year of the PhD the state of the thesis was mentioned frequently. This then became the main piece of information that had to be presented to the panel members. The writing of the thesis basically involves preparing appropriate information for each chapter, the production of a draft version and then the final version. This could be represented as PERT or Gantt charts, with each stage in each subject area as a different task. The method suggested by Prof Elder was far simpler and had been use previously. This was to place the information into tabular form, completeness of each stage being represented by a fraction or percent. This method was adopted and proved to be both clearly understood and easily prepared.

It may appear from the previous description that the use of management software was a failure when used on the PhD and that more traditional 'by hand' methods won. This may be the case to some extent, but it has to be remembered that the requirements of the management changed during the PhD and that, although not a complete success for its initial use, it did bring to the forefront issues that may have been otherwise ignored, ie. it proved to be a good 'check list' and an aid to logical thinking.

The management requirements in respect of controlling and monitoring the PhD appeared to have changed in the following way;-

i) Initially - future program needed to be clearly defined and conveyed to the members of the panel.

ii) Six months to two years - panel needed to know how the research was progressing and how the future plans had altered.

iii) Two years to end - similar to above except that the future plans diminished as time passed. Monitoring of the thesis became important.

The main advantages of management software appeared to be that it can display a future work program, then monitor its progress, incorporating changes in circumstances and times, while indicating to the user when improvements could be made to the plan. In this case management software did not arrive until well into the second phase. At this point the project was well defined, with only minor changes to its structure, such as delays. Its main advantages were therefore almost obsolete by the time the software was introduced. Had it been used from the very start the story may have been very different. For example, while the initial plans were being brought together the software would have helped predict likely durations etc and would have been considered more of an aid to planning than a method for clearer presentation once the plan was formulated. At the start the 'by hand' methods had proved themselves to be inadequate, so it is probable that use of software would have been beneficial. In the last year the requirement for planning was disappearing, so in turn were the benefits of software, although awareness of how delays affected the research may have been enhanced.

As mentioned above the use of software may have had benefits other than those initially apparent. During management courses the principles of project management were demonstrated, but when involved in a real piece of work many of these ideas were forgotten. By using software the user was presented with these ideas continually, whether they were apparent or not. As Gantt charts were produced the tasks being undertaken concurrently were exposed, together with periods where they could be moved to. Without the software this might not have been so obvious. The same was true of finding the tasks that made up the critical path, as once identified these tasks could be more carefully controlled. Although both of these examples could have been done without the use of software the chances are that little effort would be given to the task unless prompted. The hidden benefit of using software is that management techniques are re-enforced, but it should also make the manager think about planning a project at an early stage.

Management software also has its disadvantages. Time had to be spent in understanding it and in inputting the project data. Time could easily have been wasted in trying to optimise the programme too early, ie. before all the variables were known. Like most other pieces of software the user could start to over use it, producing far more information than was required. As well as the possibility of making the manager think about the project the opposite may become true. As the user became familiar with the software he may become to rely upon it. A computer program is only as good as the information it contains, so if this is at fault, either by incorrect input or because of unsuitable methods, the answers it gives will be wrong. If the user accepted them as true, without thinking about the implications or how the program arrived at them, there might be disastrous effects.

The size of a project has an important part in deciding the effectiveness of managerial software. A very simple project on its own may require no planning at all. Any time spent in doing so might take longer time than the project, although if the project was to be repeated many times any small saving might be valuable. With larger projects, which could be made up of smaller ones, thought must be given to planning, especially if there is a deadline, or resources need to be managed. With some knowledge of managerial skills a relatively effective plan should be produced. There comes a point when due to the size or complexity of the project, or other needs such as presentation to others, project management software becomes valuable. With large projects many variables and tasks may be involved. Being able to keep track of all of these would be very hard without access to software. It can also show the effect on the whole project of a small change in one area. Any time spent on this process would also be minimal compared with the project. The software user may, however, become over reliant on it, loosing effective control of the project because he sees each task as purely time and resources and not people, who need some level of understanding to work effectively.

Returning to the PhD, the size of the programme seems to warrant the use of the software, particularly because of its three year duration and because of the need for it to be clearly presented to panel members. Whether the software helped in planning seems debateable. The main resource being managed was the author's time, so it was apparent when each stage of the project was reached. It did, however, reinforce how some tasks needed to be performed early to allow work to progress at a later stage. The time and effort spent in using the software was also quite high when compared with the size of project, although if previous experience had been obtained this would have dropped considerably. The main lesson learned from this experience seems to be that managerial software must be brought into the planning of a project at a very early stage, even if not to a high degree. The software can then illustrate the likely outcome of the project and help to monitor and control it as time passes. In the case of the PhD it was implemented too late to be of any real benefit compared to the time spent on it.

In the future managerial software will be seriously considered for projects similar to this. The DRA are also now recommending the use of software for the running of programmes and it may become a requirement when submitting proposed work programmes. However, in the last year the DRA have changed their standard package to Microsoft Project. This seems easier to use than Micro Planner, requiring fewer movements around the software.

2.6 Trials management

The Plume Science section at Fort Halstead has always had a strong connection with trials work, ie. experimental work carried outside laboratories. They usually take place at a Royal Ordnance owned site at Westcott (Buckinghamshire, UK), although a few have also take place in other UK sites and occasionally abroad. Most trials basically involve ensuring that pieces of equipment are correctly set up and ready to record data for the few seconds of a firing. The data is then analyzed at a later date and supplied to the end uses. The section uses many different pieces of equipment, recording data in the millimetric, infrared, visible and ultra-violet wavebands, together with the specialized equipment currently employed for particle measurement. Experimenters from other DRA sections or outside firms may also be involved, taking varied types of measurements. The data may be used in the development of computer codes for predicting the rocket plume, the development of rocket motors (for example ensuring high thrust with low levels of detectable emissions) and for use in missile detection and recognition systems. Because of these varied requirements the trials may need to be run in different ways to ensure that the required measurements are taken. Please see Chapter 4 for a review of experimental measurements of rocket plumes.

During the period of the PhD a number of trials were performed to obtain information on particles and others attended to record infrared spatial data. By observing other peoples organisation of trials a more in depth understanding could be gained of how they could be run efficiently. The person running a trial tends not to appreciate all the problems that individual participants have, usually because of a lack of communication due to the geography of the site and insufficient time or inadequate knowledge of other's equipment. These are some of the issues that must be addressed. Most trials basically follow the same format, although there are exceptions, such as trials which take place over an extended period. In most trials the following stages have been identified as important;-

i) Initial request from a customer.
ii) Discussion with trials team on what measurements could be made.
iii) Discussion with the researcher or customer on the measurements to be made, resulting in an agreed trials specification.
iv) Trials team are informed of the specification and a provisional date set for the trial after consultation with the site manager. The relevant paper work is also completed.
v) Leading up to the trial a trials plan is issued, which outlines the measurements and defines responsibilities.
vi) During this period the state of preparation of the trials team requires monitoring and changes to the specification may be required. Any major changes would warrant a re-issue of the trials plan.
vii) Transportation of the equipment to the trials site.
viii) Setting up of equipment at the correct locations.

ix) The firings and measurements.

x) Packing up of equipment and transportation to parent site.

xi) Suitable analysis of the collected data to meet the customer's requirements.

xii) Supply of information to the customer, which will hopefully fulfil their requirements, if not further work may be necessary.

xiii) Assessment of the results and the running of the trial.

The customer may be external to the DRA or a fellow researcher requiring measurements. Because of this how each stage is carried out may vary, for example discussion may take the form of a informal discussion or a series of in depth meetings. Each stage still needs to be addressed in some way, otherwise either there will be confusion in later stages, or the requirements of the trial will not be meet.

2.7 Inadequate trials management

To show how the final methods for managing a trial were arrived at it was thought appropriate to describe examples of inadequate methodologies previously encountered. These can basically be split into two distinct types; trials which were not actively managed and those that were unevenly managed.

When the person responsible for a trial did not actively manage, due to disinterest or inexperience (maybe not of trials work, but of people), the trial followed the stages identified previously in the following way. After obtaining a request for the trial any discussion with the 'trials team' was circumvented and a trials date set after discussion with the firing site manager. The 'trials team' would then be approached. They may have had other commitments, or equipment might not be available for that date, resulting in having to return to the customer and the site manager to reset the dates. Until the trial little else was done, the state of preparation was not monitored and a trials plan not issued. The trials team would then assemble their equipment at the site, often being hampered because the site was not ready, for example no electrical power, long grass or no vehicle to position the equipment caravans. Positioning of equipment was often arbitrary, as the reasons for the trial were not disseminated. Other experimenters may become involved, wishing to position themselves in conflicting locations. This was often resolved by 'first come first served' or relative importance of the experimenter, rather than the importance of the measurement to the trial. Firing times were set at the least ambitious level. In general miss-understandings and inefficiencies built up to produce an overly long trial with low quality results. The low quality partly arises from the low morale of the people involved due to the poor coordination and long periods of waiting, often unnecessarily, combined with lack of knowledge of what measurements were required. On returning to the parent site analysis was carried out, but often there was little contact with the people requiring the information as to what they needed and no proper feedback of whether the information supplied was adequate. The person running the trial would take varying levels of interest at this stage and would not analyze how well the trial was carried out, for example by discussing it with the trials team, resulting in a similarly managed trial the following time.

Uneven management is when the level of management or control varies, making those involved unsure whether they must await instruction or use their own initiative. It may result from someone who used not to actively manage trying to respond to their inadequacies, someone who does not appreciate all the problems encountered during the trial, or someone who is normally well managed but allows their involvement to decrease, for example due to operating their own equipment or when different communication skills are required. The most usual example encountered is when the trials organiser issues fairly in depth plans before the trial, often with unnecessary details which do not allow for the competency of those involved and at some point nearer the trial relinquishes all responsibility. The trial then falls apart as no one is there to control it and the experimenters involved are either unaware of the situation or are engrossed with their own tasks. If during the planning stages it was recognised that the organiser was going to become less involved at some point, for whatever reasons, then the other participants would be able to take responsibility for their own areas. Without clearly defining areas of responsibility, confusion prevails. The only way to find out if the people involved are unsure of what is happening is to talk to them. The organiser can then respond to any deficiencies and make sure that he is more proactive next time. The organiser has to be involved throughout the period of the trial to appreciate the problems that occur and to appreciate how things can be done better.

The stages of organising a trial were identified previously, but there are also a number of basic problems that a trials organiser must address. The most important one is communication. Everyone involved in a trial needs to know what is expected of them and the other experimenters. This is usually done verbally, but often needs to be followed by a clear written description. The detail and frequency of the communication must depend on the level of changes incurred. The organiser must also listen to the experimenters, as if they are properly informed they will be able to positively contribute to the planning of the trial. They may be the only people familiar with their equipment, so they may be the only ones qualified to make the decisions, or at least advise the organiser. Communication needs to be clear, especially during the count down to a firing, when any confusion may cause loss of results. Another set of problems that are encountered are those due to unplanned changes. Although some changes cannot easily be predicted, for example freak weather conditions, others can be recognised in the planning stages and contingency made. These are such things as equipment failure for short periods, short periods of inclement weather, or changes in equipment position. Some provision needs to be made so that the trial can continue when such minor things occur, for example having available rain proof covers or spares parts for unreliable equipment.

Another area previous mentioned is that of responsibility. Each member needs to know what is expected of him and to agree that he will carry it out. This seems a simple task, but due to a lack of communication it is often missed. The importance of each set of results must also be established and should be decided by the trial's customer. When the trials specification was drawn up the relative importance of each measurement should be decided. In this way if the measurement positions conflict, or a piece of equipment fails, it can be decided whether a piece of equipment is important enough to disrupt other measurements or halt the trial.

2.8 Effective trials management methodology

While organising trials the author has tried a number of different methods of management, communication and planning. Before describing the most successful ones, the main points that need to be remembered are listed below;-

i) Effective communication.
ii) Establish the required results and their priority.
iii) Defined responsibilities.
iv) Level of planning appropriate to the task.
v) Maintain good level of morale and 'team' spirit.

The first important milestone in trials preparation is when the initial trials specification is produced. When doing this all the relevant facts and opinions from the customer and trials team need to be exchanged so that the specification is realistic and appropriate. The detail will not be comprehensive, but all the points need to be clearly defined. This can then be distributed to all those involved, with an allocation of any responsibilities already decided and a provisional firing date set. The requirements of the trial need to be stated, together with their relative importance and who the customer is. The people involved can then feedback any information, such as changes in availability, but also have to be encouraged to do so by communicating with them regularly. This may be in the form of an informal discussion, or in the case external experimenter regular phone calls. Care has to be taken to set the right level of communication, as too much will also be counter productive. The amount must be determined by the importance of the measurement and the chances of changes occurring. All members should feel adequately informed and a new specification issued if major changes occur. At a suitable interval before the trial, say two weeks, a trials plan is issued. In the past this has been too basic. The minimum that is required is; a provisional timetable showing the expected tasks and firing schedule (with firing identification numbers) together with expected slippages, an outline of the equipment and measurements to be taken with a map of their locations, allocation of all the tasks involved (this may be fairly general), a list of all the people involved (this helps the 'team spirit') and a reissue of the trials specification if necessary.

With a clear description of the planned trial the experimenters can then judge how successful their measurements will be and any adjustments can be made before they arrive on the site. During the actual trial the communication becomes mostly verbal, with notes taken by the experimenters. If complicated changes are made a written communication will be warranted. It has also been found that the use of a white board situated where everyone will see it is very helpful. The expected firing schedule can be listed on this and any changes noted. Firing times can also be written, together with basic motor information. It is important that everyone feels that they are well informed (and really are) and can easily speak with the organiser. The count downs for each firing need to be clear, with the appropriate precautions made so that everyone is ready and have the facility to stop the firing. Each experiment should be aware if their measurement is important enough to warrant stopping the firing, as delay due to minor measurements may disrupt other more important ones which may have equipment that is difficult to reset or require specific weather conditions. So that the management of future trials may be improved at the end of the trial some feedback on how the trial went should be obtained. Details of the measurements taken need to be assembled and possibly a post trial statement issued or meetings held. The experimenters need to know what analysis is required and in what form it needs to be supplied. This is usually direct to the customer, but sometimes a coordinator needs to be appointed, for example to write a post trial report.

Although the above is by no means a comprehensive guide on how to run a trial it is hoped that it illustrates the basic methodology used.

2.9 Management of future projects and general critique

The aim of this chapter was to describe the author's managerial experiences during the period of the PhD. It has been a learning experience, both in the methods that are available and in the problems that have appeared. Software was experimented with during the planning of the PhD with little obvious benefit to the research. However, as well as the hidden benefits, such as becoming more aware of managerial techniques, a greater understanding of managerial software was obtained. In the future this will allow projects to be more easily assessed as too whether the benefits of using software are larger than its inherent cost. The research seems to have been managed fairly well, as it involved varied and unproven techniques whose outcomes were to affect the course of the work. This did not mean that planning was impossible, rather that the work needed to be allowed to diverge from the plan if a different 'path' emerged.

On a more personal side the PhD has given a better understanding of how people work together. When organising people on a trial it is difficult for the organiser to remain part of the 'team'. If the 'team' feels that the organiser is external to the group communication becomes more difficult, as people almost see the organiser as a threat. A careful balance has to be maintained and the way people work has to be appreciated. Some require comprehensive instructions to complete a task, while others find them demeaning. The right balance is required, or at least some feedback from the person involved. It has also been noticed that people may often not mention a problem that they have noticed, especially when responsibilities are not clearly defined. However much planning is done such mistakes may occur and they are best corrected if people are working in an open environment, feel they are contributing and feel appreciated. The underlying theme is good communication.

From the author's experiences and courses attended the most useful maxim taken to heart is; every one has responsibilities towards the people they manage, but also to the people that manage them. It basically emphasises that people should take some responsibility for themselves and those around them. This seems very important in all people management situations. It is hoped that involvement in this PhD will make the author a more efficient, adaptable and 'human' manager. The DRA is at present under going a number of changes, the most important being a more customer orientated approach and ISO9001 quality accreditation. The author's increased awareness of management will hopefully allow better understanding of these and future changes to come.

2.10 Summary of conclusions

During this chapter different aspects of management and planning were discussed. The first half of the chapter identified the main variables and constraints encountered during the planning of the PhD. It then described the managerial techniques that were implemented, including the use of managerial software for planning and monitoring the project. The relevance of managerial software to research projects was concluded to be as follows;-

i) Time spent implementing the software must be balanced by the size or value of the project.
ii) Software should be introduced at an early stage, so that it can analyze the future work programme and allow the full benefits to be reaped as the work progresses.
iii) The software can identify short comings in the plan, ie. makes use of project management techniques which might not otherwise be implemented.
iv) Progress can be easily monitored and any changes to the plan simply added.
v) The software produces graphical illustrations of the project suitable for presenting to others (funding panels).

During the rest of the chapter the management of trials was analyzed. It was concluded that for their successful management the following were required;-

i) Effective communication between those involved.

ii) The required results and their priority needed establishing.

iii) Responsibilities needed defining for each 'team' member.

iv) A level of planning appropriate to the tasks was required.

v) The morale of the 'team' needed maintaining.

vi) Feedback from the customer and the 'team' was required to assess the running of the trial and identify any possible improvements.

3 COST-BENEFIT ANALYSIS OF THE RESEARCH PROGRAMME

3.1 The viability of the research

Any piece of research should aim to produce results that balance its cost. Even so called 'blue skies' research has the ultimate objective that the knowledge gained will be of benefit in the future. There may also be unpredicted benefits developed during research, which can then be used in other applications, such as new materials and processes. However, it should be remembered that, although these unpredicted benefits may be the most important ones after the research, before undertaking a research programme only the predicted benefits can be weighed up against the expected costs. The likelihood of realising these benefits should also be calculated so that the risk involved can be judged before investment.

If an organization has sufficient resources it may be able to fund a number of research programmes with high risk and large possible benefits, as it may believe that the overall return may be better than funding low risk research with limited benefit. If investment was restricted to low risk research with limited benefits then the likelihood of great jumps forward in technology would be small. This does not mean that because something is high risk that it deserves funding, since the returns may be low, or other areas of research may be more rewarding. How risks, benefits and costs are judged varies between different organisations, with time and with market forces. For example, a firm may need to make a large leap forward in its technology to prevent its products becoming obsolete, while any small improvements would be a waste of effort.

In the defence industry there has to be mixture of research types. When developing systems there may not need to be any high risk research, as the costs and benefits of each part of the programme can be easily judged if much of the technology is already available and needs only to be implemented. However, the technology and knowledge available may not be sufficient to allow a system to be developed that has any worth, ie. superior to current or predicted systems. To allow future systems to be developed there must therefore be a sufficient level of investment in the underlying knowledge and in basic research, ie. research in areas not directly relevant to systems in current development. Such research is inherently higher risk, as even if the research is successful it may never be applied. The costs and potential benefits should still be analyzed to indicate which programmes should be funded, or how they may be carried out more efficiently. It is therefore the aim of this chapter to analyze the research carried out for this thesis, to discuss the balance between cost and benefit, and to suggest improvements for future programmes.

3.2 Where are the benefits realised?

Before discussing the specific parts of the research it was thought worthwhile to decide where the benefits of the research are realised, ie. where in the structure of the organisation they have effect. The Defence Research Agency is a Government Agency, being part of DERA (Defence Evaluation and Research Agency), so any benefit for the DRA is a benefit for the United Kingdom. This might be realised in economic terms, for example as increased exports, or in military terms, such as having superior armaments. The advantages of such superiority might be the prevention of future conflict, or increasing the chances of winning one with lower losses. In both cases the benefit is immeasurably high.

The DRA operates as a Trading Fund and as such must create enough revenue to continue its operation. Funding is obtained by providing services to individual customers (for example the Ministry of Defence and British Aerospace). To retain customers the DRA has to maintain a lead in technology and therefore any technical advantage produced by research may increase the DRA's revenue. The same is true for any other advantage that improves the Agency's trading position, such as improved communication with other companies or a higher international standing.

The DRA is sub-divided into sectors of business, the author's being Weapons Systems. These have objectives similar to the total DRA, ie. to create enough revenue to operate successfully and must maintain a technological lead to do this. These are then sub divided into Departments (eg. Electro Optic Warfare), again with similar aims. These comprise Resource Groups and finally sections which work on specific areas of research (eg. Plume Science). It is probably at this level that any benefits of research have the greatest effect on the people producing them. The available funding for future research will increase if a section is consistently providing customers with the required services and is also able to increase its revenue or improve its standing by technical achievement.

3.3 Direct benefits from the current research

It was thought best that the benefits from the research be divided into those that directly relate to the investigation of exhaust plume particles and those which have been gained as a consequence of the research, ie. the spin offs. Benefits can be described, but it is very difficult to quantify them, as it will be their final uses that will determine how important they are.

The ultimate benefit of this research will hopefully be an improvement in missile performance. Just how much this research contributes is difficult to judge, but it is important to see in what effect it may have. Missiles can be detected or identified by means of their exhaust plume. 'Heat' seeking missiles (IR) and short range battle field missile detection (UV) systems are examples. Being able to reduce the electromagnetic signature of a missile is therefore very important and would reap large benefits for the owner. In many parts of the electromagnetic spectrum the particle content is a major contributor to the observable signature. Missiles may also require a communication link through its own exhaust plume to a control position, such as by laser or radio signal. In most cases the link may be interrupted by particles attenuating the signal. It is therefore important to be able to reduce or modify the particles in an exhaust plume for missile signature control and uninterrupted communication. As well as particles that are formed from combustion products, particles are also intentionally added to the propellant to stabilize the combustion process, for example zirconia. When choosing which additives it is important to know how they effect the flow and the plume signature. The greatest benefit to future missile design from this research is its part in the development of a comprehensive plume prediction code, allowing for two phase as well as chemical reaction, together with codes for signature and attenuation prediction. Having this facility would allow missile motors to be carefully tailored to meet performance requirements without the need of a firing programme. It would also allow the modelling of potential enemy missiles for use in missile detection and recognition systems.

Particles were collected from within exhaust plumes. They were analyzed to give size distributions, shape, consistency and the amount collected at different locations. This information is important in the calculation of plume emission and transmission. There are physical laws available for how particles affect these calculations. These require particle size, shape and refractive index. This will be of significant benefit to missile communication, detection and recognition once it is fully utilised. The information can also be used in two phase fluid dynamic codes for input values of particle size, density and drag factor (calculated from shape). The amounts caught at different positions across the plume can then be used to help validate the predicted results.

Measurements of particle velocities in plumes are also important for code validation. For single phase codes the measured velocities give some indication of the gas velocity and of plume structures, and in two phase predictions a direct comparison can be made between the calculated and measured particle velocities. There are very few reliable measurements of plume parameters, mainly due to the hostile environment, so additional data is very valuable for code development and validation.

The computational work carried out was to assess if in the future a plume code could be developed to include chemical reaction and two phase flow. The measured particle velocities were compared with the gas velocities of a single phase reacting prediction and with the particle velocities from a two phase non-combusting prediction. It was seen that, although there were common trends, a combined code would need to be developed to correctly model the flow. This is a valuable start in the work to produce such a code, but the full benefit will only be realised once a two phase reacting plume can be predicted. Such a code would be very important for the development of future missile systems, but to calculate how much the present work has contributed to this code and how large the benefit of such a code will be, is a very difficult task.

Possessing the collection and velocity measurement techniques will be important in future research as the measurement of exhaust plumes particles will be at a much reduced cost due to the developed equipment and expertise. There is considerable international interest in plume particles so the developed techniques and recorded data will also be important for the prestige of the section. This is important in discussion with other parties, as they are more likely to come forward with their own research developments if they are interested in yours. In this way the actual information gained from a piece of research may become multiplied by the addition of exchanged information and therefore increase the benefits.

3.4 Spin off benefits

During the period of the research various different technical areas had to be studied to find which techniques could be used in the exhaust plume environment. Once the knowledge had been gained other areas in which it can be implemented appeared. Benefits were also gained by the use of facilities, both for the section (and therefore the DRA) by the availability of rocket firings to other researchers and by outside firms that received payment or increased their own knowledge.

The collection and analysis of particles is not exclusive to rocket exhaust plumes. There is interest in collection from jet turbine exhausts, while collection from aircraft flares has already taken place. Although a flare is of a smaller scale and typically of lower velocity the Centrisep technique worked well. Being able to do such collections obviously increases the sections ability to obtain funding from areas away from exhaust plumes. Any research undertaken would hopefully increase the expertise in particle collection, which may feed back into future rocket exhaust work. Having such a facility available to the DRA is important, as future researchers need not develop their own collection methods, but instead make use of ours at reduced cost. The manufactures of the Centriseps and filters have also benefited from the research. Previously they had not used the equipment in such hostile environment and having proof that they can survive in a rocket exhaust helps in future marketing.

In characterising the collected particles various techniques for obtaining particle size, composition and appearance were investigated. The limitations of using scanning electron microscopes had to be appreciated, ie. that only elemental informational was provided together with pictures of the particles, leaving the compounds present and the size distribution unknown. The use of X-ray diffraction to provide more in depth chemical information (ie. the compounds and their crystal structure) and laser diffraction for size analysis, filled this gap. Acquiring this knowledge of particle analysis complements the developed particle collection methods and means that any prospective customer can be provided with a complete service from collection to interpretation of the results, although the actual analysis would still need to be performed outside of the section. It should be noted that the full expertise of the people carrying out the analysis is still very important, as their experience cannot be overlooked. These analysts have also benefited from the work in income and by increasing the types of particles they have encountered.

The anemometer system used for the velocity measurements was originally used for measuring of gun muzzle velocities. Its new use for plume measurement has increased the range of environments that it can be used in and has renewed interest in the system. The involvement of AEA Technology (Atomic Energy Authority) in the equipment has meant that they are aware of the system whenever customers ask them to make measurements and may in the future want to rent the system to carry out measurements in other flow fields. The same is true within the DRA, as there may be future work for the system. In this way it is hoped that the system may be utilised more than it has been in the last few years.

The benefits of the programme were not all linked to particle research. On each rocket firing trial other experimenters where invited to make measurements to increase their own knowledge of exhaust plumes or of their equipment. For example when particle collection was taking place on the CRV7 motors, long distance measurements were also being done in the ultra-violet and infrared to compare with measurements taken over shorter ranges. In this way the expense of firing the motors was made better use of by allowing other experimenters to benefit. During the course of the research facilities were used at Royal Ordnance Westcott and at Cranfield. In both cases it is hoped that more people will become aware of the capabilities of each site through the present research and make use of them in the future. This is particularly important in the case of Westcott, as the Royal Ordnance is in the midst of a rationalisation programme. The Plume Science section relies heavily on these sites for measurements on static rocket motor plumes, so maintaining their operation is beneficial.

Being involved in a PhD programme allowed access to the members of staff at Cranfield University. This benefited all areas of the work, as their technical input and different experiences complimented the expertise of the DRA. To obtain this in any other way would have been very expensive, for example by paying Cranfield for the time its staff spent on the project. The time spent on attending panel meetings was used as an estimate of the probable cost. Approximately six meetings occurred each year, three Cranfield personnel attended for five hours each time and they would cost roughly £40 per hour.This totals £10800 that the DRA would otherwise have had to pay. The PhD also attracted funding from the Engineering and Physical Sciences Research Council in the form of grants to the DRA which totalled £13500 over the three years. The contact with the university may have also helped in obtaining funding from the Strategic Research Programme for £100K during 1994.

All the benefits mentioned in the previous two sections are summarised in section 3.7, where a critique of the costs and benefits is given.

3.5 Marketing the benefits

The previous sections outlined the benefits that the current research has yielded. In many cases the full benefit will be lost unless people are made aware of them and they are made use of in the future. While performing the research people became aware of its existence, but this cannot be relied upon to disseminate the information gained. In the future there needs to be a strategy of presenting the benefits of the research, ie. the information gained and the existence of a section capable of carrying out future particle research. Only in this way can it be fully made use of, ie. it needs to be marketed. The most direct ways of increasing the general awareness of the work is by presentation at seminars or by publication. In both cases the event or journal needs to be carefully chosen so as to target people with an interest in the subject. The Institute of Mechanical Engineers would appear to be the most suitable society to help in the task, as they have a monthly journal and hold a biannual international seminar on flow measurement techniques. There are a number of journals covering aspects of rocket exhaust research that may be interested in publishing part of the work, such as Combustion and Flame, and Rocketry and Spacecraft. Again it is unknown whether the present research would be of sufficient interest to the bulk of their readership and further investigation is required to find out if the research can be written into a form that might be acceptable to the journals.

On becoming published or presented at a seminar the research would probably appear on international data bases, together with this thesis. This means that in the future researchers seeking information in this field would be able have access to the work. The main disadvantages of these methods is that the people who may prove most valuable to any future research may be missed, ie. the possible future customers or assignment managers. This group of people are mostly DRA or Ministry of Defence employees and although they may be keenly interested in their own areas of research, for example missile seeker technology, they may not read the journals that a 'plume scientist' might think most relevant. Internal publications may be able to help, or indeed more general aerospace journals, such as Flight International, but the type of article would probably only be a summarising paragraph or based on one aspect of the work.

The best way of approaching these customers seems to be to increase their awareness of exhaust plume particle research through personal contact and word of mouth. Personal contact encompasses; meeting other researchers, sending out copies of reports to people who may be interested, presenting work whenever possible and in general making the information easily available directly to other researchers and possible customers. The 'word of mouth' aspect is very important, as it is often found that information is most easily spread to the relevant areas by people discussing the work and suggesting it to others. Being involved in international collaboration groups is important, as it allows direct contact with researches in the same field and gives the work more credibility internally. Applying to receive funding from a customer may end in rejection, but during the process of choosing which projects are worthwhile the people involved become more aware of the work and may be able to offer funding for future applications or suggest collaboration with others working in related areas. The DRA is in the process of constructing at 'knowledge network' into which each employee can register his areas of expertise and business contacts. Hopefully in the future this will increase the visibility of the research and will make it easier for people presently doing research in related fields to make contact.

The information gained is very important for the development and validation of computer predictions. To make the most of the data it needs to be presented in such a way that it can be easily used by researchers in their work. Reports on measurement data may prove the best way of doing this, each one being a set of particle data for a validation case. The codes themselves will need to be marketed so that full use is made of them. This may be done by performing the predictions for customers or by licensing the software. Similar methods for disseminating the information about the codes will be required to those suggested for the previous research.

3.6 The cost of the research

Most of the research cost was born by a Strategic Research Programme and an Applied Research Programme, the funding for both originating at the Ministry of Defence. The DRA's training budget paid for a fifth of the authors wages and the PhD fees, but in return the DRA received a grant from the Engineering and Physical Sciences Research Council. To establish the total cost of the research and the areas in which it occurred, all expenditures have been listed in Tables 3.1 to 3.7. The costs have been divided into different types of expenditure and into the research areas in which they were incurred. In this way it was hoped that the benefits already discussed could be compared with the relevant cost and that by identifying where the expenditure occurred it may be minimised in future.

The total expenditure over the three years was £306K. The costs involved with the research were divided up into those related to buying merchandise (£64K, 21%), to extramural research work or services such as firing motors (£86K, 28%) and to man power effort (£156K, 51%). Where appropriate these costs have been allocated to areas of research. In the case of merchandise the £64K was divided up into five areas. The largest proportion was trials equipment used for more than one task (56%), which was mainly rocket motors. Various different measurements were usually taken when a motor was fired, so the cost could be shared between participating projects. Equipment used purely for particle collection accounted for a further 21% of the merchandise expenditure (Centriseps and filters). The proportion spent on velocity measuring equipment was 17% and was mainly due to purchase of the traversing table, as the anemometer was borrowed. During the period of the PhD a PC version of PHOENICS was purchased (the code used for plume predictions). The cost of this has been included as, although this code was used by other researchers, use was also made of an already purchased UNIX version which has the additional combustion coding. It was therefore thought that the cost of the PC version reflected the true cost. At £2.5K this was 4% of the merchandise. The remaining 2% was spent on general items.

The costs incurred on extra mural services and research work were similarly divided up. This time a larger proportion was spent on velocity measurement (65%), as this involved three contracts with AEA Technology for operating the system. The other expense was the firing of the rocket motors, which involved payment to the Royal Ordnance for their services. 18% of the services was spent on particle collection, the majority being the firing of motors and the rest the cost of the particle size analysis by Malvern Instruments and MCA. The cost of Royal Ordnance firing two motors for recording their infrared and ultra-violet signatures made up 5%. The remaining 12% were the fees paid to Cranfield by the DRA. These were included as they are the cost involved with Cranfield's involvement in the research.

The man power effort has been divided up into the people involved. Obviously the largest proportion was the author's time at 86%. Ron Lawrence, who was the industrial supervisor, accounted for 9%. DR G.A.Jones is the head of the Plume Science section, so was involved in defining the direction of the work and in obtaining the necessary funding, which accounted for 2% of the cost. Mr M.Baker performed the Scanning Electron Microscope analysis of the particles at Fort Halstead. This was charged at the same hourly rate as Ron Lawrence, even though it involves the use of a very expensive piece of equipment. The SEM analysis cost £4K (3% of the man power effort), nearly the same as the cost of the size analysis by Malvern Instruments for a similar number of samples. It should be noted that the cost of the man power included the persons wages, a charge for the facilities used and overheads. The people involved were also charged out at different rates according to their seniority.

Finally in Table 3.7 expenditure of all types has been divided up into the main research areas. The trials equipment that had previously been non-specific has been proportioned equally between velocity measurement and particle collection. The man power effort, with the exception of Mr M.Baker, has been divided up into 40% on both velocity measurement and particle collection, and 20% on computer predictions. A more precise division could not be done because much of the work was relevant to more than one area. The time spent on the managerial content of the PhD has not been shown, as it was really spent in organising the research work, so has been included with it.

It can be seen that the expenditure on velocity measurement was higher than on particle collection (£148K, 48.5% compared to £109K, 35.5%). This was mainly because of the higher cost of the measurement technique, which outweighed the equal division of the man power effort. There was a slightly greater merchandise spend on particle collection, but this was insignificant compared to other costs. The 11% spent on the computer predictions was mostly made up of the man power effort, which was an estimate, although the figure appears to be representative of the work produced. 2.5% was spent on the fees for the PhD, which seems very low in comparison with the influence that it has had on the work. This does not, however, include the time spent in attending PhD panel meetings etc, which has been included as part of the research, as it was the research that was being discussed. Any other cost that was incurred, for example on obtaining infrared signatures, amounted to 2.5%.

In summary;-

Research area	Expenditure	
Velocity measurement	48.5%	£148K
Particle collection	35.5%	£109K
Computer predictions	11%	£34K
PhD fees	2.5%	£8K
Miscellaneous	2.5%	£8K

Total		£306K

3.7 Critique of the costs and benefits

The aim of this section is to analyze the balance between the costs and benefits of the research, and to suggest improvements in the management of similar research programmes. The main benefits from section 3.3 and section 3.4 are summarised below, but have this time been split into the present benefits and the possible future benefits. The costs have already been summarized above in section 3.6.

Benefits (present);-

- Plume particle data (from collection and velocity measurement).
- Particle collection and velocity systems established for plume and other research.
- Improvement in knowledge of predictive codes.
- Understanding of particle analysis procedures.
- Information available for 'exchange'.
- Maintained reputation of the section.
- Rocket firings available for other researchers.
- Support of facilities.
- Access to Cranfield staff.

Benefits (future);-

- Reduction of plume signature, ie. the detection and recognition of missiles.
- Improved missile communication.
- The above give rise to improved missile systems which will be an important asset to the DRA and the country.
- Increased funding for future research.

The objectives of the research listed in section 1.2 have been fulfilled by the research work undertaken and the writing of this thesis. Basically the objective was to gain information on plume particles and to direct future research. So it is this that should balance the expenditure. The other benefits, such as those mentioned under spin offs, may be just as important for the DRA in terms of revenue. It is very difficult to quantify how much the present research has contributed to the ultimate aim of the research, ie. to improve missile systems and predictions. Normally a comparison between actual costs and estimated monetary benefit would be presented, but to estimate these benefits would be purely subjective, depending very much ones attitude towards defence work. It was therefore thought more appropriate to mention previous researchers work and how they compared in cost and benefit. As the ultimate benefits cannot be calculated a measure of how the research has contributed is the amount of information it has produced.

Two research programmes have been identified for comparison. They were of different size, but both occurred in the same time period and were based on exhaust particles from the Space Shuttle. Strand 1981 describes research to establish the effect of Space Shuttle launches on the environment. It was assumed that data from smaller rocket motors could not be extrapolated to larger ones, so several Titan III rockets were fired (40% the size of a Space Shuttle motor). It was not stated if these firings were funded by the programme, but the instrumentation would have been. Particle collection was performed using sticky tape impactors carried by a helicopter and a U2 aeroplane. Even if the expense was shared the cost to the programme must many times greater than that of the PhD work. The information gained on the particles produced by the firings seems limited, as there would have been a considerable size bias introduced by the collection methods and the precipitation of the larger particles. However, the objective of the work was to measure the environmental effects, rather than gain plume data, and although the methods were expensive, there appears to be no real alternatives. The research lacks any information about the particles inside the plume, which would have been a valuable starting place for predicting the particle content in the surrounding atmosphere and unless the expenditure for aircraft was shared the ratio of results to cost seems poor.

The second programme was of a much smaller scale. The objective was to discover the whether chloride formation on the surface of alumina particle produced by the Space Shuttle was common (see Cofer 1984 for details). Samples were collected from the structure used to launch the Shuttle and from the wings of a light aircraft which had passed through the exhaust cloud. Relatively large quantities were collected and were then analyzed to provide the necessary data. Laboratory experiments followed using alumina particles and HCl to gain a better understanding of the reaction. Sensible conclusions are drawn at the end, the main limitation being that samples were not gathered from higher altitudes. This work seems to have produced good scientific data, suitable for basing future work on, and at a reasonable cost. The ratio of results to cost seems better than in the other research programme.

In both cases it appears that the cost was related to the collection methods used. The lower cost of the chloride investigation is therefore matched by a lack of upper atmosphere data, although some indication was given by the inclusion of laboratory work. The research carried out for this PhD seems to have produced more data than either of these examples (in each case the value of the data is difficult to estimate) and it appears to have a good ratio of results to cost.

Another measure of how effective a programme has been is to study if the expenditure could have been spent more appropriately by using cheaper or more rewarding alternatives, or improving utilisation. Again this is very subjective. Most measurements are passive, so utilisation can be improved by increasing the number of measurements taken during each firing and wherever possible this was attempted. The collection and velocity measurement equipment obscured or intruded into the plume, making other measurements inaccurate. It was also found that increasing the number of other measurements caused an increase in the complexity of the trial, causing more delays and allowing less time to be spent on the main activities. Therefore a balance had to be made between increasing the benefit of a firing by increasing the measurements and decreasing the benefit due to the risk of poor particle measurements.

One way of increasing the information gained would have been to fire more rocket motors. Although more data would be available, the present data was as much as could be analyzed and understood properly in the inherent timescale. In the future data can be collected with less risk of failure, as the information previously gained can be used in the preparation of the trial and in the prediction of the results. Trials can be tailored to provide more specific information for plume code development and validation. Performing fewer firings would have reduced the costs, but the information gained would have been incomplete and insufficient to make a proper assessment of the research.

In reviewing the costs it was seen that the largest one was the time spent on the research and additionally the cost of the services/research work was mostly man power. This is to be expected in research work unless expensive equipment is purchased, and it must be here that any major saving in cost can be made. By increasing the time management skills of those involved a saving could have been made, but in general it was thought that time was not wasted during the research, ie. work was not repeated unnecessarily or schedules arranged badly. A saving may have been made by improved control of contractors carrying out the services and research work. In both cases the work was carried out to specification, but with hindsight these should have been more detailed and unambiguous, although some flexibility was required. Time was also wasted due to the processing of the required contracts which slowed down the work causing a lost of momentum and necessitated a change of schedule. The possibility of lowering the cost of merchandise seems unlikely as every effort was made to reduce costs, for example by ordering Centriseps when the unit cost was low (when the firm had concurrently received a large order) and by making use of available equipment, for example borrowing the velocity measuring system.

The costs were separated out in to which area of research they were attributed to. The cost of the velocity measurement was slightly higher than the particle collection. This seems to be represent well by the benefits gained from them, as both have produced important information on particles and provided a sound base for future work, and although the particle collection produced more data, the velocity measurements were more unique and involved higher risk. The collection work seems to be most adaptable to other applications, but the velocity work may prove to be most important for plume code validation. The cost of the computer prediction work was much lower, but may have been higher if more time had been available, although an important start in combining the chemically reacting and two phase coding was made, and particle phenomena seen experimentally simulated.

In conclusion it is thought that the cost of the research is out weighed by the present benefits and in the future they may be multiplied many times over. It is unlikely that the costs and benefits could have been greatly improved, although in the future their importance to a research programme should not be forgotten.

4 BACKGROUND TECHNICAL INFORMATION

4.1 Plume science - the study of rocket exhaust phenomena

A rocket exhaust plume is a region of high temperature gases and particles ejected at high velocity from a rocket motor. Due to the conservation of momentum, the motor experiences an opposite force to that accelerating the flow (ie. the thrust). Most rockets are designed with a convergent-divergent nozzle which causes the flow to exit the motor supersonically. The plume gases decelerate to subsonic velocities via a number of shocks. If the velocity is high enough the initial shock may be normal to the flow, otherwise it will be oblique, as will the following shocks. Air becomes entrained into the plume, which causes any unburnt fuel to combust (termed after burning or secondary combustion). Particles present in the plume affect the flow field by transferring mass, momentum and energy between the phases. Plume science is important militarily due to the effects of plume characteristics on the ability of missiles to carry out their missions. The study of plume science involves the understanding, prediction and control of these characteristics, such as plume emission and propagation properties.

Exhaust plume emissions are important for missile detection and recognition (AGARD (1994) and Davenas (1993) both describe the subject in depth). The main wavebands of interest are the microwave (2-300GHz, not often used), infrared (700nm - 14μm), visible (400nm - 700nm) and the ultra violet (100nm - 400nm). The mechanisms that produce the radiation vary, but are generally affected by the plume temperature. Charged species are the main source of microwave radiation in the plume. The infrared signature is dominated by emissions from CO_2 and H_2O molecules (notably the red wing, at 4.6μm and the blue spike at 4.2μm), but there may also be peaks caused by CO, HCl, HF and N_2O. The presence of such peaks in an emission may identify the chemical composition of the motor's propellant and in some cases identify the missile. When molecules present in the plume are also present in the atmosphere they strongly absorb the emissions, as emission and absorption processes are linked (for example the absorption of CO_2 emissions at 4.3μm by atmospheric CO_2). Plume particles emit right across the infrared waveband (thermoluminescence, producing a continuum emission), but are most noticeable in the 8-14μm region where molecular emissions are low. The visible region is also influenced by particle continuum emissions and the emission lines caused by chemical species, most notably the sodium D doublet (at 589nm), the potassium doublet (at 767nm) and CaOH band (at 623nm, possibly contributed to by CaO).

The ultraviolet part of the spectrum is split into three regions. Emissions in the near ultraviolet (300nm to 400nm) are from hot particles and chemiluminescent reactions of $CO+O \rightarrow CO_2$ and $OH+H \rightarrow H_2O$. There are no emissions from thermally excited species, since the energy required for excitation is not available at normal plume temperatures. In this waveband atmospheric absorption is low enough to allow measurement from a reasonable range, but the contrast against the background is poor due to solar emissions. In the mid ultraviolet (200nm to 300nm, the solar blind region) atmospheric absorption limits any measurements to short ranges, but it has the distinct advantage that natural background radiation is very low. Particles are the main emitters in this waveband, which is also true in the far ultraviolet (or vacuum ultraviolet, 100nm to 200nm), where the atmospheric absorption is so high that emissions can only be detected in near vacuum conditions.

In some missile systems the propagation of radiation through the plume is used to communicate guidance information, as described in JANNAF (1977). The radiation is usually at radio or infrared frequencies and may be absorbed by the plume gases, although attenuation by plume particles scattering and absorbing radiation may also be significant. Such particle scattering is dependent on particle size, refractive index and number density and can be predicted by use of the Mie or Rayleigh scattering equations.

One of the main aims of plume science is to be able to predict plume characteristics and their effect on missile systems without having to carry out measurements. This enables the cost of motor development to be reduced, and is necessary to establish plume properties under flight conditions or when a motor is unavailable. Chapter 7 deals specifically with plume prediction, but in general the following must be taken into account; the fluid dynamics of the flow (use of the Navier Stokes equations, with the inclusion of turbulence models), the chemical reactions of species present (use of rate equations for the possible reactions) and two phase flow effects (these will affect the previous two). Axial symmetry is assumed for most plumes, which simplifies the predictions by allowing the plume to be modelled as a two dimensional flow field.

The flow field prediction is important in its own right for applications such as missile airframe interactions and damage to missile launchers, but is more commonly used in application codes to predict plume emissions and propagation. An example of an application code is BANDIR (Ridout 1978), which models the infrared emissions of the predicted plume gases. The code calculates the emission and absorption of radiation along a line of sight between the plume and the observer, although the code makes no allowance for the particles present (the flow field data used is solely gas phase). Codes are also being developed for the ultra-violet region, where the contribution from particles can be even more significant.

4.2 The importance of plume particles

4.2.1 Effects on the plume flow field and on predictions

The presence in a flow field of a second phase of material means that there will be a transfer of mass, momentum and energy between the phases. The energy may be kinetic or thermal, and may be transferred by processes such as drag, conduction or radiation. Particles maybe solid or liquid droplets and may have different temperatures and velocities to those of the gas phase, especially in regions where the plume contains large gradients, such as near to the nozzle or through shocks. These differences are termed "phase lags", as the values of one phase tend to lag behind those of the other. This will tend to smooth out any discontinuities in the flow and slow down any divergence, ie. reduce the rate of energy loss from the plume to the surrounding air. The particles also affect the turbulence in the gas phase, as the lag in velocity dampens local velocity perturbations. Turbulence in a rocket exhaust plume is important because it influences the mixing together of the plume gases and the entrainment of the surrounding air, both of which effect the combustion processes in the plume, such as secondary combustion.

Plume particles may also combust, increasing the temperature of the particles and the gas. These changes in temperature may affect the particle's density, size and shape, for example by reaching a melting point, and also determine whether or not the particles conglomerate (cemented together) or agglomerate (fused together). These processes must be included in an accurate prediction of a plume with a particle content. Consequently it is essential that particle characteristics are measured for use in the development and validation of predictive codes. Influential particle characteristics include velocity, temperature, size, density and drag factor (or shape). The importance of particles to the plume flow field and its prediction can be summarised as follows (See Booth (1989) for mathematical derivations);-

i) The addition of particles decreases plume expansion.
ii) Both phases maintain higher centre line velocities than for a particle free flow and cause shock features to be dampened.
iii) The particle velocity lags are greater for larger particles.
iv) The particle velocity differences decrease with increased particle number.
v) The turbulent kinetic energy decreases with the addition of particles.
vi) The Reynolds shear stress for a two phase plume is less than that for a particle free one (because of the possibility of velocity difference between phases).
vii) Reduced thrust, due to the reduction in gaseous species (ie. lower chamber pressure).

4.2.2 Observed effects on plume emission measurements

The importance of particles on rocket plume emissions has been demonstrated by measurements of static motor firings. To show the greatest difference between flows with high and low particle content two versions of a Canadian CRV7 motor were chosen, each having a similar thrust, nozzle dimensions and chamber pressure. The C14 version had a composite propellant (mainly ammonium perchlorate), with 18% of aluminium added to increase the specific impulse, which causes alumina particles to appear in the plume. The C15 version was similar, but with no added aluminium and therefore fewer particles. For operational reasons the thrust of each motor has been designed to increase over the duration of the firing. The results can be compared at points where the thrust levels are common. See Appendix A for motor details.

Figure 4.1 and 4.2 show the results from an ultraviolet spectrometer. It should be noted that the irradiance scales used are vastly different and that the irradiance of the C14 plume was forty times larger than that of the C15 plume. Apparent peaks in the C15 result were mostly due to increased system noise, caused by the higher system amplification required to make the lower emission level of the C15 measurable. The most important feature was the abundance of radiation in the ultraviolet solar blind region in the C14 plume compared to little from the C15 plume (a region presently of military interest). This may not have been entirely due to increased particle numbers, as the temperature of the C14 plume was higher, which would have increased particle temperatures and gas chemiluminescence.

Figure 4.3 and 4.4 show results obtained in the visible region. Again the scales on the graphs differ and the C14 plume emissions were sixty times greater than those of the C15 plume. Peaks due to sodium, potassium and CaOH were detected in the emissions from both plumes. In the C14 plume the magnitudes of these peaks were over fifty times higher, even though the level of the emitting impurities (borne in the ammonium perchlorate) had dropped, due to the accommodation of the aluminium in the propellant. The rise in radiation must therefore have been largely due to increased gas temperature resulting from the added aluminium.

Infrared spectral measurements (Figure 4.5) showed that the emissions from the C14 plume were higher than the C15 by a factor of between 2 and 4. This was due to increased gas and particle temperatures in the plume, as well as increased particle numbers. Figures 4.6 and 4.7 show infrared spatial measurements of the C14 and C15 plumes. The C14 plume equivalent black body temperatures were significantly higher in both of the wavebands used for measurement. These measurements were analyzed to give equivalent black body radiant intensities (ie. a measure of the energy emitted by each plume in the direction of the observer). The C14 plume produced 13,675 $W/sr/m^2$ in the 2.11 to 5.42μm waveband and 2,980 $W/sr/m^2$ in the 8.11 to 12.36μm waveband, while the C15 plume produced 4,807 $W/sr/m^2$ and 704 $W/sr/m^2$ in these wavebands. There was therefore 2.8 times more radiation emitted by the C14 at the shorter wavelengths and 4.2 times more at the longer ones, illustrating the importance of particles in the 8 to 14μm region of the infrared. Some of the emissions shown in Figures 4.6 and 4.7 were due to the 'searchlight' effect, mentioned in more detail in 4.2.3, where particles travelling near to the plume's centre line scatter radiation emitted from inside the motor.

4.2.3 Processes by which particles can effect plume emissions

Particles produce detectable emissions in the ultraviolet, visible and infrared regions of the electromagnetic spectrum. More research has been carried out in the infrared due to its military importance, although many of the phenomena involved are also relevant to other wavelengths. Particles directly contribute to plume emissions by emitting continuum radiation, but they also indirectly affect emissions by increasing the gas temperature (for example by initiating secondary combustion or by transferring thermal energy to the gas) and by scattering radiation from other sources. Continuum radiation is dependent on the particle's temperature, surface area and emissivity. This means that a given mass of smaller particles at a certain temperature will emit at a higher rate than larger ones of the same total mass, although because of their more rapid energy loss they may be extinguished faster. Smaller particles often appear to radiate less in the plume due to their rapid cooling, while much larger ones can sometimes be seen as bright specks at comparatively long distances from the exit plane.

The effect of particles on secondary combustion is reported in Kraeutle (1991) and (1992), where aluminium oxide and carbon particles were added to an oxygen/hydrogen plume. This showed that a previously non burning plume could be ignited by the addition of particles, but that a burning plume showed a drop in emissions, caused by the effect of the particles on heat transfer and turbulent mixing. As particle concentration was increased in the burning plume, emissions began to increase, although emissions from the particle content did not rise (ie. the emissions were gaseous). When carbon particles were used the greatest increase in emission came when the chamber temperature was increased to above 2300°C. At this temperature the carbon began to combustion and particle emissions became more significant than gas emissions. This study was based on a fairly ideal plume, for example there was probably little nozzle erosion, but the basic principles are still important in operational motors.

Radiation from sources outside the plume can be scattered by plume particles, notably solar radiation in the near ultraviolet. The mechanism of scattering is dependent on the optical properties of the particle, its size and its shape. Plume particles will also scatter radiation emitted inside the plume or motor. The searchlight effect, often mentioned in the description of plume measurements, is caused by the scattering of the radiation emitted from inside the nozzle or combustion chamber and allows these emissions to be observed at oblique angles around the plume. Reed (1992) described the phenomena in more detail, for example the effect of particle size and chamber radiation, and also showed that the searchlight effect may contribute thirty percent of the total radiation between 2-5μm for an aluminised composite motor. Nelson (1984) gave an in depth theoretical study on the influence of particles on plume emissions. The majority of plume particles were efficient scatterers at the shorter infrared wavelengths, as their diameters were similar to the wavelengths, while at wavelengths over 10μm scattering decreased. Particles are usually considered to be more important as emitters in the 8-14μm infrared, where plume gas emissions are low by comparison, but also contribute significantly in the 2-5μm waveband when particle loading is high (ie. in aluminised motors). Since scattering depends on the wavelength of incident light and the characteristics of the particles present, spectral variations in scattered light may be observed. Boynton (1968) illustrated how radiation emitted as a continuum from the nozzle may be changed spectrally by selective scattering in the plume.

4.2.4 Effect on transmission and other phenomena

The influence of particles on the transmission of radiation through the plume depends on their number density, size and refractive index. Communication links passing through the plume may be attenuated by particles, so it is therefore important to know their characteristics and to be able to change them. Plume particles form the primary smoke trailing a missile, which maybe added to by secondary smoke (for example condensed water and HCl droplets from ammonium perchlorate propellants). This smoke may disrupt communication signals and scatter radiation from other sources, for example ultraviolet radiation from the sun. Kessel (1985) describes how the transmission characteristics of the plume can be measured by shinning a source of known frequency (ie. a laser) through the plume onto a detector.

Particles have a number of secondary effects. They may erode the motor's nozzle causing the expansion ratio to decrease and the motor's performance to change (with possible changes in plume emission). The use of inert particles to reduce combustion instability requires careful optimisation, since the inclusion of non-energetic material causes an increase in missile weight or a reduction in the motor's impulse. When a missile is fired the launch vehicle must not be damaged or disadvantaged, for example the primary smoke (ie. exhaust particles) trailing behind a missile may indicate to an adversary the location of the launch position. Contamination of the environment by the efflux from large rocket motors can also present a problem, especially when particles reside in the atmosphere for a considerable time.

4.3 Types of rocket propellant and sources of particles

4.3.1 Requirements of a good propellant

Rocket propulsion commonly uses liquid or solid propellants. Combustion is achieved with most liquid propellants by mixing two or more reactive liquids together (an oxidising agent and a reducing agent), resulting in an exothermic reaction. This is performed inside a combustion chamber and the resulting gases expelled through a nozzle to produce thrust. Because of their liquid nature any two phase phenomena will probably be restricted to liquid droplets rather than solid particles. Experimental firings of liquid motors and literature on the subject do not indicate solid particle formation. Future work may confirm these findings, but during the current research only solid propellant rocket motors will be considered.

Solid rocket propellants must be of reasonable cost, but also have good physical and mechanical properties that allow the safe formation of the charge. When fired they must have the required burning characteristics and energetic performance, ie. steady thrust and high specific impulse (thrust multiplied by firing duration and divided by propellant mass). They must also produce a plume with the required signature and propagation properties. While the missile is being stored the propellant must remain safe and have a long shelf life. The basic fuel and oxidant used in a propellant will have the largest effect on these properties, but over the years various additives have been found that improve certain characteristics. Although beneficial in some ways these additives are harmful in others, for example adding aluminium as a fuel increases the thrust of a composite motor, but also increases plume emissions. As the propellant and its additives are a major source of plume particles they require investigation. The remainder of this section describes the composition of solid propellants, outlining what additives are added and why, and how they may effect the particle content of the plume. Mention is also made of other sources of particles, such as the motor lining material and igniters. Information from Davenas (1993) was used to produce a detailed list of propellant additives which appears in Tables 4.1 and 4.2.

4.3.2 Double base propellants

One of the main improvements in rocketry occurred in the late 19th century when nitrocellulose and nitroglycerine were combined together to form a high energy propellant which was relatively safe. This was called double base propellant and can be manufactured into shapes by extrusion or casting. The technical description is a propellant whose binder consists of a energetic polymer (nitrocellulose, 40-70% by weight of the propellant) which is plasticized with a nitric ester (nitroglycerine, 15-41% of the propellant). The energetic level of the nitrocellulose varies with the level of nitration of available hydroxyls. All the elements required for the release of energy are available in the same molecule. The propellant has good mechanical, ageing and burning properties, little primary smoke (ie. particles), very little secondary smoke (droplets/particles that are formed down stream of the plume) and the possibility of a low observable signature. 5-10% of a double based propellant consists of additives which give rise to many of the previously mentioned properties. These additives are the main source of particles, although carbon particles may be produced from the nitroglycerine or nitrocellulose and there may be fragments of ablated nozzle or liner.

During manufacture plasticizers are added to aid gelatinization and change the mechanical properties. Phthalates or triacitates can be used which also desensitise the nitroglycerine, ie. improve handling safety. Graphite is added in small quantities to help the flow of casting powders (possible particle producer), while Candelilla wax and magnesium stearate are added to help in the extrusion process (possible particle producers). Unless treated, the propellant slowly decomposes over time, with $O\text{-}NO_2$ bonds being broken in the process. This produces nitrogen oxides which catalyse the reaction. Organic stabilizers, often containing benzene rings, are added to prevent this reaction, as without a stabilizer the propellant may become unsafe due to the exothermic reaction, which may cause cracks to form and decrease the energy available for propulsion.

The burning rate of unmodified double based propellant is highly dependent on pressure. If uncontrolled this would be catastrophic for the motor, as increased burning would increase the pressure further, eventually ending in failure. Ballistic modifiers are added to maintain a stable equilibrium of burning and pressure (termed a plateau and the additives are also called burning rate catalysts or platonization agents). They also have the effect of reducing the dependency of the burning rate on temperature, allowing performance to be maintained over a range of combustion chamber temperatures. These additives are usually metallic, so are likely to appear as particles in the plume. Examples are lead oxides, lead salts (including stearates), copper salts and acetylene black (which also increases the effect of the other salts). The amount of these additives must be carefully controlled as they affect the releasable energy, the burning rate, the pressure level, the properties during manufacture and may also produce plume particles. An alternative way of increasing the burning rate is to incorporate silver or copper wires perpendicular to the burning surface. They allow a path of heat flux into the propellant, raising its temperature and thereby its burning rate. The wires melt and oxidise before expulsion from the motor, forming particles in the plume.

Other additives are collectively called "operational additives", as their addition depends on the operational characteristics required. The most common produce a stable burning rate, which will in turn provide the uniform (or predictably changing) thrust required for most missiles. They are usually particles, such as zirconia, zirconium silicate or silicon carbide, and appear to work in two ways. Their presence in the burning surface of the propellant provides a path for the conduction of heat below the surface. This helps to maintain a steady advance of combustion through the propellant and means that the main variation in the level of combustion in a homogenous propellant will be due to the surface area exposed. This means that specific thrust characteristics can be achieved by moulding the propellant into different shapes. The simplest is a solid end burning charge (cigarette burner) which provides a near uniform thrust. The motor's thrust can be raised by increasing the burning area of the charge, for example by forming the charge in a tubular configuration with a hollow centre. If the centre of the tube is circular, the burning area, and therefore the thrust, will increase as the charge recedes. By contouring the tube's internal surface a uniform thrust can be produced (for example star shapes). Other shapes, or combinations of shapes, can be used to produce required levels and variations in thrust. These shapes include;- slotted, trumpet, rod and cylinder, concentric rings and dendritic. Refractory particles (ie. those that remain solid at high temperatures) also attenuate acoustic effects in the combustion chamber that would otherwise produce combustion instability.

Another group of operational additives are those that affect the rocket plume. Most plumes are fuel rich and may combust on mixing with the oxygen content of air entrained into the plume. This is obviously undesirable for military missiles because the burning will raise the plume temperature and increase the level of emissions. Small quantities of flame suppressant are added to the propellant (commonly potassium salts, such as cryolite, sulphate, bitartratre and oxalate), which provide a fast reaction route to remove combustion sustaining free radicals from the plume.

4.3.3 Composite propellants

Composite propellants consist of at least two compounds and have the oxidising and reducing atoms present in different molecules. Metal powders may also be added to increase the energetic content, while the composite structure is directly relevant to how the propellant burns. Composites offer the possibility of a better performance and allow the manufacture of much larger charges due to the ease of casting (eg. the Space Shuttle's boosters). The biggest improvements in motor performance have been due to better reducing agents that also bind the propellant together. Originally solids that required melting by a heating process were used, such as asphalt or polyvinyl chloride. In the early 1950s new liquid binders were introduced, and in the mid 1960s liquid binders with a functional polybutadiene base were developed which allowed greater solids loading and manufacture at lower temperatures. Common examples are acrylonitrile-acrylic, acid-butadiene, acrylic, acid-butadiene co-polymers and homoploymers with functional ends, while polypropylene, polyether, polyester and polysiloxane have also been used (all are unlikely to produce particles other than carbon). The oxidising agent was originally potassium perchlorate or ammonium nitrate, but these have mostly been replaced by ammonium perchlorate. This is available in a choice of particle sizes, which allows the burning rate to be modified (1-400μm diameter).

Because of the composite nature of the propellant a number of additives are used to produce the required curing characteristics. The molecules of the polymers used in the binder require an agent to help them link together. These cross linking agents influence the mechanical properties of the propellant, but are usually purely organic and used in very small quantities. Plasticizers are required to improve the mechanical properties of the binder while liquid and after setting. Commonly oil based, they function by reducing the friction between polymer chains, which in turn improves viscosity. Bonding agents, such as triethanolamine, are added to improve the wetting of the solids by the binding material and to improve the strength of the binder/solids bond. Catalysts may also be added to reduce the curing time of the binder and improve the mechanical properties by orientating the polymer network. Organic salts of transition metals, such as tin, iron and chromium are often used and may appear in particles collected from the plume. To increase the time propellants can be stored, additives are used that slow the rate at which the charge decomposes. Such decay is detrimental to the mechanical properties of the charge, which might lead to failure during firing, although the energetic properties may remain. These additives are usually antioxidants such as phenols or aromatic amines.

Additives can also modify the propellant's burning characteristics. To increase the burning rate, chemicals are added that accelerate decomposition of the perchlorate, or lower the temperature at which decomposition occurs. They are usually organic metallic compounds containing copper, iron, chromium or boron. Originally these were in solid form, such as iron oxide and copper chromite (all are possible particle producers), but now liquids have been introduced that give better dispersion and also act as plasticizers. Given time these liquids tend to migrate, so in the future it is hoped to graft them into the polymer chain. Sometimes burning moderators are required. In non-aluminised propellants the decomposition of ammonium perchlorate can be slowed by the addition of alkaline salts or alkaline-earth solids to give up to a 50% reduction in burning rate. Another way of moderating the burning is to add 'coolants', which can also work with aluminised propellants, but can adversely affect the specific impulse. Acoustic or pressure stabilizers are not often discussed for composites, probably because of the inclusion of particle forming material for other reasons (ie. as fuel), although zirconia or silicon carbide can be used.

Supplementary to the oxidizers already mentioned other solids can be added to the binder to increase the energetic properties of the propellant. HMX and nitroguaidine (the latter also reduces the burning rate of ammonium perchlorate propellants) are two non metallic oxidisers available. The energetic properties can also be increased by adding fuels, which usually burn to form oxides or chlorides. Many different metals can be used, although the most common by far is aluminium, which burns to form alumina particles (aluminium oxide). Aluminium has good energetic properties in relation to its volume and mass. It is also suited to high levels of solid loading and has a protective oxide layer that makes it safe to handle. The carbon and hydrogen available in the binder have significant advantages over metallic fuels due to the gaseous nature of their combustion products.

4.3.4 Other sources of particles

Metal impurities that are present in propellants may form particles, namely compounds of sodium, potassium and calcium. There are other ways in which materials can enter the plume. Entrained air can carry with it many different types of material, such as sea water or particles from the surroundings, but is usually beyond the control of the motor designer. The motor ignition system is normally exhausted early in the firing and consists of flammable powder, wiring and casings. Particles may be formed during erosion of the nozzle, which may be made of carbon or organic resin with high temperature resistance. The motor casing is usually of aluminium alloy or a composite structure (eg. wound graphite or Kevlar fibres in a binder), but is unlikely to contribute to the plume unless the motor's liner has burnt through. Liners are usually organic in nature (eg. phenolic resin) and are used to protect the motor casing from the high temperatures of the burning propellant. They are normally ablative (ie. they burn on exposure) and may produce particles. After the propellant has been consumed the liner sometimes continues to burn, producing larger particles due to the lower temperatures and velocities present. Some propellant charges are wrapped in aluminium foil (to prevent damage during handling) which oxidises to form particles. Other substances are used during the construction of the motor, such as glues and fillers.

4.4 Review of previous research

4.4.1 Method of locating previous research

Information on exhaust particles was initially gathered from within the DRA and from outside contacts. A number of publications were discovered, including reports on research performed by the DRA under its previous designations. The main source for gathering published information was via literature searches using the key words; rocket plume particles, particle velocity measurement, particle pyrolysis or burning and two phase flow. More specific searches were also performed, for example the use of Global Doppler Anemometry systems.

Literature searches where carried out of the Fort Halstead library (March 1992) and of the Defence Research Information Service (DRIC) data base. This produced a number of unclassified and classified titles from the UK, other NATO countries and Japan. Of nearly one hundred titles identified only nine proved relevant. The material also seemed biased towards US Government sponsored research. It was felt that there was still a large amount of information still to be accessed and that this could be found in civil library listings. The inter library system at Cranfield was used to search through a number of UK university library holdings and located titles published by AGARD, AIAA, NASA, NACA, ONERA and JANNAF, as well as UK university papers. The Cranfield University library system was used to search the NTIS and COMPENDEX indexes to find papers published outside the UK. Supplementary searches were also done by the DRA's Information Centre at Fort Halstead through their INSPEC, NTIS and COMPENDEX directories, although a second search by DRIC found no additional information (November 1993).

Much of the data discovered by these searches is referenced in the thesis under the relevant subject areas. However, so that the reader may have access to information gained on plume particles not utilised in the thesis and become familiar with previous research, a brief resume follows.

4.4.2 Previous particle characterisation (except optical properties)

A very comprehensive paper was given by Hermsen (1981), bringing together particle collection data from sixty six different aluminised composite propellant rocket motors (from 3 to 20.9% aluminium by weight). The particle size quoted for each case was the diameter of a particle with average volume (D_{43}), which varied between 0.25μm to 12μm. Factors such as combustion chamber pressure, chamber residence time and nozzle expansion ratio were reproduced so that any correlation with particle size could be noted. When the experimental data in the report was examined it appeared that the collection methods varied and were mostly made outside the plume. Only seven samples were collected using intrusive probes and in these cases the D_{43} diameters ranged from 1μm to 5μm. In all of these cases particle size was measured using a scanning electron microscope (SEM), but only two of these measurements were automated using an image analyzer. Because of the probability of statistical error in measurement unless vast numbers of particles are examined and possible differences due to different method or operator, only the automated measurements were thought to be reliable by the present author. The D_{43} particle diameters for these two were similar at 5.23μm and 5.77μm, although the motors from which they originated differed in design and in propellant aluminium content (21% and 18% respectively). Averaging all the data in the paper resulted in a similar diameter size and it was apparent that as much variation can occur due to collection and measurement technique as due to motor variations.

Strand (1981) describes measurement of the exhaust from the Space Shuttle using helicopters fitted with sticky tape collectors. This gave D_{43} results averaging $0.01\mu m$, far below that reported in Hermsen (1981) where a probe collector was used in similar plumes. In this case the analysis method appears to be in error, as the text mentions that larger particles were observed by SEM. A number of different alumina particle sizes were mentioned in JANNAF (1977). The particle size with the best supporting evidence (based on research reported in Kraeutle 1976) was an average diameter of $0.2\mu m$ and a D_{43} diameter of $5.6\mu m$. Carbon particles were also mentioned and were believed to be much smaller than those of alumina, with an average diameter of between 0.02 and $0.08\mu m$. A number of models were also included that tried to predict the various sizes reported. Traineau (1992) described particle sizing using optical and collection devices that made use of helium quenching to cool the particles. A $7\mu m$ D_{43} particle diameter was mentioned for an aluminised propellant and a bimodal size distribution with lobes at approximately $1\mu m$ and $6\mu m$ (on a graph of volume of particles collected against particle diameter).

4.4.3 Research on particle formation

Particle pyrolysis or burning has been traditionally studied in relation to coal furnaces (Kang 1991 is a typical research paper). Ingebo (1970) describes an experiment on burning aluminium and magnesium particles in a high velocity hydrogen/oxygen flame (66 and 254m/s). It was observed that the front surface of each particle melted first, followed by erosion of the liquid metal and combusted in the particle's wake. The oxide particles formed during this process had diameters much smaller than the original particles. In a rocket motor aluminium particles may have finished burning before experiencing these velocities (ie. in the combustion chamber), so may not break up in this way. Smith (1993) described how an oxide 'cap' may form on the droplet's surface, which may then become detached to form separate particles. Eventually droplets will become fully oxidised, or solidify with a metal core. Spherical shapes will tend to dominate because of their lower surface energy when liquid.

The oxide particles may undergo further processes after formation. Oliver (1991) and (1992) describes the formation of aluminium oxide with an initial gamma phase crystal structure (cubic - called spinel). On being held at high temperatures the structure changes to form an alpha phase crystal structure (hexagonal - called corundum) and on cooling the material does not revert (the half life of the gamma phase is 200μ seconds at 2230°C). In the plume larger particles cool more slowly than small ones (due to their smaller surface area to weight ratio), so are more likely to undergo this process. The paper states that plume particles with a diameter over 5.4μm retain their thermal energy (ie. high temperature) long enough for this to occur. The two phases have similar physical properties, gamma phase being 10% lighter and having a visible refractive index of 1.65 instead of 1.78, although some predictions may be sensitive to these variations.

Composite motors often contain ammonium perchlorate in their propellants, which burns to form HCl gas in the plume. This dissolves in condensed water to form hydrochloric acid, which reacts with any particles present to form a chloride layer on their surfaces. This may be very important as optical properties are determined by the particle's surface material. Cofer (1978) describes a laboratory experiment where alumina particles were reacted with HCl/H_2O in a nitrogen flow and indicates some of the variables that need to be considered in the reaction, such as a time dependency, which may limit the chloride formation in the short life of a plume. Cofer (1984) describes the analysis of particles collected from the Space Shuttle's exhaust cloud and from its launch tower. There was up to 11.7% chloride present in some collected samples, although the average was only 2%. In laboratory tests the alpha phase alumina (ie. the larger corundum particles) proved to be unreactive with hydrochloric acid, while the reaction of the remaining alumina (ie. gamma phase) was controlled by the concentration of acid present and the time that the particles were exposed. In smaller plumes the exhaust products are quickly dispersed, so chloride formation may be very limited, although this phenomena may be very important when calculating the scattering caused by primary smoke.

4.4.4 Measurement of particle optical properties

For operational reasons visible and infrared wavelengths are often favoured for guidance, tracking and target acquisition, so the optical properties of plume particles at these wavelengths are important. On searching the available literature a number of refractive index values were found for exhaust plume materials (measured on stationary samples). In Gal (1973) real and imaginary parts of the refractive index were given for alumina between 0.5μm to 22μm at temperatures of 300, 1000, 1500, 2000, 2500 and 3000°K. These values were so called thin film ones (from the method used to measure them) and some interpolation was used. This reference also made use of a particle scattering prediction code and included work on ice spheres, solar scattering and the searchlight effect. Another set of data appeared in JANNAF (1977) for wavelengths between 0.5μm and 6μm and temperatures of 1200, 1500, 1600, 1700 and 2020°C. This also mentioned how impurities may affect the refractive index. In Bishop (1985) refractive indices were given for possible plume materials at wavelengths of 0.4μm and 14μm. These materials were; aluminium (in two spherical particle forms and one flaked form), nickel flakes, aluminium oxide (a commercial form called Aloxite 50), silicon dioxide powder, calcium carbonate powder and carbon (so called Carbon Black).

The optical properties of particles have also been measured whilst the particles were suspended in a gas flow. In Chippett (1978) and Charalampopoulos (1987) measurements were made of soot particles formed in both propane and methane flames, while Eiden (1971) describes a measurement made on aerosol spheres. Measurements made in conditions representing a real plume were described in Konopka (1983), where particles collected from rocket plumes (mostly alumina) were measured in a stream of heated Argon gas. Temperatures of between 1726 and 2959°K were used, and wavelengths of between 1.30μm and 4.50μm. This work suggested that the optical properties were highly dependent on surface contamination, although above the melting point (2330°K for alumina) the bulk properties become dominant. The particles' surface or structure may have altered from that on collection, as they were reheated.

Plass (1964) made use of aluminium oxide and magnesium oxide values of refractive index in Mie scattering calculations. The values available at that time were limited to room temperature for the real part and 1000°C for the imaginary, and did not agree very well with Gal (1973) for imaginary values above a wavelength of 5μm. This paper showed that sub-micron aluminium oxide particles were efficient scatters below wavelengths of approximately 5μm, the efficiency dropping off significantly by 10μm (efficiency being expressed as the ratio of scattering cross-section to particle cross-sectional area). Increasing particle size improved the efficiency at higher wavelengths, although the number of particles per unit mass rapidly decreased.

5 PLUME PARTICLE CHARACTERISATION

5.1 Review of particle characterisation techniques

5.1.1 Introduction

Plume particle characteristics need to be measured for use in computational codes that predict plume flow field and electromagnetic phenomena. Ideally measurements of particle size and shape should be made non-intrusively using optical techniques, although they must contend with the effects of the plume emitting, absorbing, scattering and diffracting electromagnetic radiation. The instrumentation required is also complex, expensive and requires an experienced operator. The intrusive collection of particles involves relatively simple techniques such as filtration, but the particles may be damaged during collection or the flow field changed by the intrusive device. Collected particles can then be analyzed to reveal information on the particle composition, shape and size. Before experimentation could begin, possible characterisation techniques were reviewed in order to determine the one best suited to the present application.

5.1.2 Intrusive characterization techniques

Techniques for collecting plume particles were found in published literature, but the level of operational success was not often apparent. Misener (1983) describes various proposed plume diagnostic techniques, but gives little indication of the previous success in rocket plumes. Other papers quoted results from plume particle collections, but did not describe the collection techniques in adequate detail for proper assessment, notably JANNAF (1977) and Hermsen (1981). Particle collection techniques used in other types of flows were also investigated, for example air filtration, but they were not often suited to the extreme temperatures and velocities of rocket plumes.

To simplify the assessment of the various collection techniques they were divided into categories according to the gas velocities they were suited to. The following performance criteria were also formulated;-

- Must survive in the plume environment.
- Have a collection efficiency independent of particle size and velocity.
- Cause negligible damage to the particles.
- Collect enough particles for the results to be representative of that location and to allow analysis.
- Cause minimal disruption of the flow.
- Measure the spatial variation of particle size in the plume.
- Costs should be in proportion to the benefits.

(i) Total exhaust capture technique

Rocket motors are fired in low pressure chambers to simulate high altitude operation. Particles present in the plume are deposited on the internal surfaces of the chamber and can be collected mechanically at the end of the firing. Such collections have been performed by ONERA (France), but the quality of particle sample was poor due to the dependency of particle deposition on the time after the firing and the position in the chamber. The method is susceptible to contamination from previous firings in the chamber (proper clearing is difficult) and there is also a lack of information on the spatial variation of particle characteristics in the plume.

A suggested variation of this technique is to use a large heat retardant fabric bag instead of the chamber. The bag would have to be large enough to hold all the plume gases, or alternatively act as a filter to allow gases to escape, leaving the particles behind. Due to contamination the bag would need replacing after each firing, although its size could be reduced if motors of low thrust and short duration were used (a volume of $25m^3$ would be typical).

(ii) Low/zero velocity techniques

These are commonly used for the measurement of particles present in the atmosphere. The University of Manchester Institute of Science and Technology (UMIST) have developed a system for monitoring atmospheric particles and aerosols (Smith 1993). The sample is drawn through tubing from the measured region into instrumentation which measures the size and number of the particles present. By heating the sample in the tubing any aerosols present can be evaporated off so that only the solid particles are measured. Particles can also be collected for further analysis as they exit the instrumentation.

A simpler technique is the use of sticky surfaces onto which particles can become attached. Traineau (1992) reported successful collections using this method and Strand (1981) improved upon this method by the use of electrostatic forces to attract the particles onto the surface. Stand's collection device also periodically exposed clean sections of the sticky surface so that the temporal variation could be measured. Both Traineau and Strand collected particles in the exhaust clouds left by very large rockets (the Space Shuttle) where greater quantities of particles were present than in the plumes available to the author. A size bias may occur using this method due to the physical processes involved in the attachment of the particles to the surface. The collected particles may not be representative of those present inside the plume, for example larger particles may have fallen out before collection could occur. Trials work by the author revealed that the technique was unreliable at the edges of the plume due to the low numbers of particles collected and contamination from the surroundings. The technique is therefore only suitable when it is not possible to collect particles inside the plume.

(iii) Subsonic techniques.

Sticky plates have been used for collecting particles inside rocket exhaust plumes. The collected particles had a size bias, due to the tendency of particles with higher drag or lower weight to not become attached to the plate and instead follow the flow field due to aerodynamic effects. When the flow velocity is significant a filtering method is more appropriate, so long as the pressure loss across the filter is kept low enough to prevent the flow diverging around the device. A steel filter can operate at plume temperatures of up to 1500^{0}C (its melting point) and ceramic filters even higher. Filters with relatively small frontal areas could be positioned across the plume to provide information on the spatial variation of particle characteristics.

Another method of particle collection is by centrifuging the particle/gas mixture so that the particles are separated out while the gas escapes unhindered. The Centrisep (Figure 5.1) is a commercially available device which makes use of this principle to remove particles from such flows as the air feeds to aircraft cabins and the intakes of helicopter gas turbines operating in desert conditions. They consist of a cylindrical tube through which the gas and particles flow. Internal vanes spin the mixture and the resulting centripetal acceleration causes the particles to move towards the cylinder's wall, where they pass out through a side vent. Particles can be collected by attaching a filter to the side vent. Pressure loss through this filter will have little effect on the flow through the Centrisep. The manufacturers quote a pressure loss through the Centrisep of approximately 5% (Lewis 1993) and that approximately 5% of the gas leaves via the side vent, carrying with it over 90% of the particles. There is, however, no performance data for transonic or supersonic velocities, as the design is optimised for subsonic flows, but it is anticipated that the collection efficiency would be severely degraded if supersonic effects were present, such as shocks.

(iv) Supersonic techniques

The techniques described in the previous section can be used in supersonic regions if the flow is decelerated to subsonic velocities at the point of collection. Ideally the flow velocity must be reduced slowly so that the particles are not damaged by strong shocks. Misener (1983) describes an arrangement for a supersonic collection probe where the flow inside was decelerated through a convergent divergent nozzle before filtration

(Figure 5.2). A tungsten tip was used on the probe to withstand the hostile conditions and cold nitrogen gas was used to solidify molten particles. The design of supersonic probes must account for shock structure forming outside the entrance of the probe as well as the deceleration of the internal flow.

As well as adapting subsonic designs there are techniques that rely upon supersonic flow for their operation. Misener (1983) suggests a second device that makes use of a Prandtl Meyer expansion fan formed on the leading edge of a probe (Figure 5.3). The plume gases and particles are deflected by the expansion fan, but the particles are deflected by different amounts according to their size and density. This causes the particles to separate out in the region behind the probe. Collectors or erosion bars in this region are used to record the spatial particle concentration present, thus enabling the plume particle size distribution to be determined. However, the operational success of such a device could not be ascertained.

5.1.3 Non-intrusive sizing techniques

There are a number of parameters that can be measured non-intrusively, for example particle size, number and velocity (Chapter 6 deals with velocity techniques). Measuring particle parameters in situ is superior to intrusive methods where particle characteristics may be altered during collection or storage, but they require a higher level of expertise and expenditure. Intrusive measurements are usually limited to slower regions (ie. subsonic), while non-intrusive techniques maybe capable of making measurements throughout the exhaust plume.

Laser Doppler anemometry allows the measurement of particle velocity and size simultaneously (Farmer 1978). An interference pattern is created at the measurement position by the crossing of two coherent laser beams. The pulses of light scattered by particles passing through the regions of constructive interference are detected and then analyzed to give particle velocity and size. The technique is, however, limited to velocities below those typical of rocket plumes (section 6.1.2 gives details of velocity measurement).

Misener (1985) describes measurement of particle size with a transmissiometer consisting of a 4 watt argon ion laser and a silicon photodiode detector. Measuring the light scattered by particles in different directions can be used to accurately determine the particle size, although particle refractive index must be known. This technique is similar to those used in the laser diffraction particle sizers (as in section 5.4.2(iii)) where a number of detector positions are used. The technique has been used for plume measurements with some degree of success (Traineau 1992) and can be used to measure particle refractive index if particle size is already known.

Particle sizes can also be measured using imaging techniques such as Particle Image Velocimetry (PIV) and Global Doppler Anemometry (IMechE (1992) describes both). The use of these systems for velocity measurement are discussed in section 6.1.5. In general the image is produced by illuminating the particles in a flow field with a laser sheet and recording the image with a high speed camera or video. Particle velocity, size and shape can then be determined by image analysis. If the period of time taken to record the image is sufficiently small particle size and shape can be measured at relatively high particle velocities.

5.1.4 Selection of techniques for plume particle characterisation

Intrusive and non-intrusive particle characterisation techniques can be summarised as follows;-

(i) Intrusive techniques

- Collected particles can be analyzed later to determine their size, shape, number and chemical composition.
- Techniques can be developed at a lower cost and risk.
- The collected material may not be representative of the plume, as particles can

be damaged on collection or whilst reaching ambient conditions (ie. cooling).

- The local flow field may be disrupted.

(ii) Non intrusive techniques

- In situ measurements with high spatial resolution could be made of particle size, shape and number.
- The flow field remains unchanged.
- The techniques are usually complex, requiring an experienced operator, and may prove unsuitable for rocket plumes.
- Particle chemical composition cannot be measured.
- Techniques using scattering phenomena rely on estimates of particle refractive index.

Intrusive characterisation seemed most appropriate for exhaust plume measurement during the present research because of the limited time scale and funding available, as well as the advantages of obtaining particle chemical composition and having a greater possibility of success. It was decided to make particle collection in the subsonic areas of the plume to avoid supersonic phenomena. The total plume capture method (section 5.1.2(i)) was too costly and offered poor results, while the low/zero velocity methods (section 5.1.2(ii)) were deemed unsuitable because of the predominance of high velocities in the plume and their lack of spatial resolution. The subsonic techniques (section 5.1.2(iii)) offered two techniques which had good spatial resolution and reasonable chances of success. The Centrisep had the advantage of causing less disruption to the flow, although the filtering method (the 'in-flow' filter) offered simplicity and lower cost.

5.2 Particle collection proving trial

5.2.1 Aims of the trial

A proving trial was performed to demonstrate the 'in-flow' filter and Centrisep techniques in a rocket exhaust plume. The aims of the trial were as follows;-

i) To establish if collection was possible in the plume.

ii) To assess the techniques' relative particle collection efficiencies.

5.2.2 Apparatus and method

The filter material used in both types of collector was grade H Hasteralloy porous sintered stainless steel (PSS) which can withstand high temperatures (1500^{0}C), high pressures, filter to below 1μm and can be manufactured in a variety of sizes. The 'in-flow' filter holders consisted of two parts threaded together with the filter clamped between them (Figure 5.4). A stainless steel Centrisep was purchased with an internal diameter of 80mm (Figure 5.6 and 5.7). Particles exiting the Centrisep through the side outlet were collected by a filter held in a holder of the same design as the in-flow filter collectors. The Centrisep was supported in a stainless steel cradle mounted centrally on a steel girder and an in-flow filter collector positioned either side. The girder was fixed to a large steel frame positioned behind the rocket motor (Figure 5.8).

Ten firings of an Experimental Aluminised Composite motor were performed at Royal Ordnance Westcott for another research project on which the collection equipment could be used. These motors had a composite propellant containing 12% aluminium (known to produce a high concentration of particles) and an initial thrust of approximately 18kN, which dropped to 12kN by the end of the 2 second firing. A detailed breakdown of propellant composition can be found in Appendix A. The collectors were positioned at various axial positions during the firings (Table 5.1) and became contaminated after each firing, so required thorough cleaning before reuse (using nylon brushes and high pressure water and air). New filters were used for each firing as effective cleaning was impossible.

5.2.3 Results and discussion

Both methods survived the exhaust environment, although the apparatus became discoloured by the high temperatures and showed signs of erosion (Figures 5.5 and 5.6). Particles were collected at all the positions and by both types of collector. On average the Centrisep collected 5 grams of particles during each firing, while the in-flow filter technique collected significantly less (although the amount was roughly proportional to the smaller intake area). A larger in-flow filter may collect more particles, but the collected particle sizes would be biased by the increased disturbance to the flow (the flow may diverge and pass around the outside of the collector). Scanning electron microscope (SEM) analysis could not detect any difference between the particles collected by the two techniques and showed that the majority of the particles were spheres of an aluminium compound. The particles had diameters ranging from 0.01 to 100μm and appeared undamaged by impact with the filter or Centrisep (ie. fragmentation). The collected samples were fully analyzed at a later date, the results of which can be seen in section 5.5.2.

5.2.4 Conclusions

The Centrisep collected particles in sufficient quantities for analysis at all the experimental positions attempted. The collected particles ranged from 0.01μm to approximately 100μm in diameter and showed no signs of fragmentation due to impact with the collectors. The location of the Centrisep in the plume was limited by the gas temperature and by the supersonic velocities. The in-flow filter method collected particles comparable with those collected by the Centrisep, although in smaller amounts that were insufficient for proper analysis. The in-flow technique cost approximately 90% less, so could be used in greater numbers and in high temperature regions of the plume where severe damage to the collector was probable. The collection efficiency of the Centrisep still relies upon manufacturer's data, as the quantity of particles present in the flow during collection was not known, although a wide range of particle sizes were collected and collections were made at different plume locations. Particle collection was therefore possible with both techniques, although each one had its own merits.

5.3 Seeded Heavyweight motor and CRV7 trials

5.3.1 Introduction

This work involved two separate sets of firings (also known as trials). The first trial involved firing six specially manufactured Heavyweight motors (Heavyweight refers to their case construction) and a Cast Double Base motor (CDB - military issue), while six CRV7 type motors (again military issue) were fired on the second trial. Appendix A shows the motors' propellant constituents and thrust characteristics.

On the first trial velocity measurements were also made using an optical technique (Chapter 6). The propellant constituency of the Heavyweight motors was accurately known and included small amounts of refractory material (zirconia or silicon carbide). The collected particles could therefore be compared with the materials present in the propellant. An estimate of the Centriseps particle collection efficiency could also be made by comparing the weight of collected particles (with suitable manipulation) with the weight of the particles in the propellant. Five Centriseps were used so that particles could be collected at different radial positions during the same firing. Although the Centrisep had proved superior in the quantity of particles collected the in-flow filters were also used as they could provide additional data for nominal expense if they collected sufficient particles for analysis.

The second trial used C14 and C15 versions of the CRV7 rocket motor (used in Canadian air to surface missiles). Both versions have a composite propellant, but the C14 has 18% of aluminium added and the C15 has a small amount of zirconium silicate.

5.3.2 Apparatus and method

The basic support rig from the proving trial was retained, but additional fixing points for five Centriseps and five in-flow collectors had to be added (Figure 5.10 shows the positions). Since large quantities of particles were collected on the proving trial it was decided that smaller Centriseps would collect adequate material and provide better spatial resolution. The design of the new Centriseps was similar to that used previously except that the internal diameter was only 48mm. The Centrisep supports were made taller than before to reduce any effects on the collection caused by the disturbed flow around girder (Figure 5.9). Smaller filter holders were required for the Centrisep outlets and were of similar design to that used in the proving trial. These held 10mm diameter filters, as this size was roughly equivalent to the original ratio between Centrisep internal diameter and filter diameter.

The diameter of the filters for the in-flow collectors was kept at 25mm, as a larger diameter would cause excessive blockage to the flow, while a smaller one would definitely collect insufficient particles for analysis. A new design of filter holder was used, which was basically a stainless steel cylinder with simple aerofoil section walls (to reduce drag) and a filter supported internally (Figure 5.5). The filter was held in place by a retaining ring which slipped into the cylinder after the filter and the filter holder itself was positioned in the flow by a support similar to the Centrisep's. Every effort was made to clean the collectors between firings (using hot water and brushes, followed by compressed air) and new filters were used for each firing.

5.3.3 Firing programme

Heavyweight motor trial

All the collectors were positioned 1.5m axially downstream from the motor's nozzle and spread at different radial positions across the plume (Figure 5.10). The firing programme for this trial was as follows;-

Firing 1 Cast Double Base motor (CDB)

Firing 2 Heavyweight motor seeded with 2% zirconia.

Firing 3 Heavyweight motor seeded with 2% zirconia.

Firing 4 Heavyweight motor seeded with 1% zirconia.

Firing 5 Heavyweight motor with no seeding.

Firing 6 Heavyweight motor seeded with 2% silicon carbide.

Firing 7 Heavyweight motor seeded with 1% zirconia.

CRV7 trial

The axial and radial locations of the particle collectors varied during this trial, as shown in Figure 5.10. The firing programme was as follows;-

Firing 8 C15 non-aluminised composite, 1.5m from the nozzle.

Firing 9 C15 non-aluminised composite, 2.5m from the nozzle.

Firing 10 C14 aluminised composite, 2.5m from the nozzle.

Firing 11 C14 aluminised composite, 2.5m from the nozzle.

Firing 12 C15 non-aluminised composite, 2.5m from the nozzle.

Firing 13 C14 aluminised composite, 1.5m from the nozzle.

5.3.4 Results

Table 5.2 and Figures 5.15 to 5.19 show the weights of particles collected by the Centriseps during the Heavyweight trial, while Table 5.3 and Figures 5.21 and 5.22 show the weights collected during the CRV7 trial. During the firing of the CDB motor only two of the Centriseps collected sufficient particles for analysis. Few particles were collected by the in-flow collectors as the filters had rotated parallel to the flow during the firing. This was prevented in the subsequent firings by the use of a small amount of cynoacetate glue to firmly position the retaining ring, although the quantities of particles collected were still too small for proper analysis. In firings 2 and 3 the Centriseps collected more particles, but after firing 3 it was noticed that the filters used in the Centrisep outlets were loose, allowing some particles to escape. On rectifying this with a suitable spacer the collection efficiency appeared to be much higher in firings 4 to 7.

The CRV7 trial started with the collectors placed 1.5m axially from the nozzle, as during the firings of the Heavyweight motors the collectors were undamaged and collected sufficient particles for analysis at this distance. A non-aluminised C15 was fired first, as its plume temperatures were expected to be lower than the C14's, but temperatures were still too high and caused damage to the central Centrisep and in-flow filter. These had to be removed, but were not replaced. However, the collectors positioned away from the centre of the plume were undamaged and collected particles. To reduce the temperatures encountered the downstream distance was increased to 2.5m for firing 8 (the second C15 motor) and the outer most in-flow collector repositioned in the centre of the plume to help ascertain if a Centrisep could survive there. No additional damage was incurred by any of the collectors during this firing and the subsequent firing of a C14 motor (firing 10, again at 2.5m). It was decided that it was important to collect particles nearer to the nozzle of the C14 motor, so the axial distance was reduced to 1.5m on firing 11 (the second C14). As expected this resulted in severe damage to the central in-flow filter.

Particles had not been collected near to the centre of the plume in the previous four firings and it was apparent that the only centre line position where Centriseps could survive was at 2.5m downstream from the nozzle (ie. where a in-flow collector had survived). Therefore on firings 12 and 13 the collectors were positioned at 2.5m downstream from the nozzle and their radial locations altered to include a near centre line position. No further damage occurred during the firing of either the C14 or C15 motors. During all of these firings the in-flow filters collected insufficient particles for proper analysis. The cumulative damage incurred to the collectors during the course of these measurements can be appreciated by comparing Figures 5.11 and 5.12 (ie. before and after the trials programme). The hostile environment of the plume flow field is illustrated by Figures 5.13 and 5.14 which show a typical firing of a CRV7 motor.

The analysis of the collected samples can be found in section 5.5.

5.3.5 Assessment of Centrisep collection efficiency

An estimate of Centrisep collection efficiency was obtained by comparing the amount of added particles in the propellant (ie. the seeding) with the collected weights, making use of the assumption that these weights were representative of the plume. This neglects the possibility that particles may have been present from other sources, such as nozzle erosion, and that there may have been localised variations in particle concentration. The collection efficiency was derived using the method outlined in Table 5.4 and Figure 5.20 for Heavyweight firings 2, 4 and 6 (2% zirconia, 1% zirconia and 2% silicon carbide respectively). The possible error associated with this method was fairly high due to the relatively large distance between data points (a 20% over estimate of the calculated collected weight of particles was possible), although if other more advanced methods were used, such as curve fitting using polynomials, they would also be open to significant error due to the large increase in particles collected towards the centre of the plume. The CRV7s were not considered as the propellant composition was not as accurately known.

It was estimated that the Centriseps collected 92% of the seeding material from the 1% zirconia motor, but only 39% from the 2% zirconia motor and 33% from the 2% silicon carbide. There was therefore a significant drop in calculated efficiency with higher seeding levels. A possible explanation for this was that the centrally located Centriseps had become completely filled with particles during the firings (this had been observed whilst removing the collected particles) and could therefore not have collected more particles when higher seeding levels were used, resulting in a lower efficiency. From Table 5.2 it can be seen that collection by the outer Centriseps did not always increase with higher seeding levels. The 2% zirconia firings were possibly inaccurate due to loose filters in the Centriseps, but by the 2% silicon carbide firing this was corrected. The main reason for this apparent loss of efficiency may be that the collected samples were not representative of the plume, due to localised concentrations of particles. The silicon carbide particles were also larger than the zirconia ones, which may have caused them to disperse less and therefore remain in the central region of the plume.

5.3.6 Conclusions on the collection equipment

Particles were collected at various locations across the plume. The particles appeared undamaged on inspection by SEM (ie. not fragmented) and diameters from 0.05μm to over 100μm were collected (see section 5.5.2). The collection efficiency of the Centriseps was limited by the capacity of the filter holders, which can easily be remedied in the future. The best estimate of Centrisep collection efficiency in the plume was 92%, but due to apparent local concentrations of particles the efficiency was also calculated to be as low as 33%, although this still represents a substantial proportion of the propellant particles. Equipment was melted if positioned too close to the motors, especially on the centre line, although this could be alleviated by the use of other types of materials, such as ceramics, increasing the thickness of the parts (ie. the thermal capacity), improving the design to prevent localised heating, cooling the gases up stream of the Centrisep, or by cooling the Centrisep.

The in-flow filter collectors did not collect enough material for proper particle size analysis or for efficiency calculations to be worthwhile, although SEM analysis showed they collected similar particles to the Centriseps. They were also no better than the Centriseps at withstanding higher temperatures. They are therefore limited to flows with high particle concentrations or when an expendable collector is required.

5.4 Particle analysis techniques

5.4.1 Introduction

The rocket exhaust particles needed to be analyzed to obtain the following information;- size, shape and chemical composition. Various analysis techniques were assessed in order to ensure that the analysis was carried out accurately. The number and type of analyses that could be performed were limited by the small amounts of particles collected, so it was important that the right techniques were chosen before proper analysis started. From initial analysis by SEM the plume particles were believed to range from 0.1μm up to 100μm in diameter and were mostly jaggedly shaped or spherical.

5.4.2 Particle analysis techniques available

(i) Sieve analysis

The simplest technique for measuring particle size is by sieving with a mesh of known hole size. The fraction of a sample of particles that passes through a particular sieve corresponds to those particles whose dimensions in one plane are smaller than the mesh's holes, although in the other plane they may be much larger, as is the case with cylindrical particles. If particles are spherical the mesh size can be related directly to their diameter and by using a number of sieve sizes the fraction of particles in different size ranges can be found. There are many standard sieves sizes, but the recognised minimum standard measurement size is about 75μm (Allen 1968) and because of this the technique was unsuitable for the current application.

(ii) Sedimentation

Sedimentation is another traditional technique and relies on the rate at which different sized particles settle in a liquid. Stokes law is used to predict the speed of sedimentation and assumes that the particles are spherical with known density and that gravitational forces are dominant. If the particles are non-spherical then an incorrect measurement will result, although some shapes can be partially accounted for, such as plates or cubes. Smaller particles ($<1\mu$m) can also be affected by the electrostatic forces (Brownian motion) which alters the sedimentation rate. It is estimated that the technique has a 20% error in measurement for 2μm diameter particles and 100% for

$0.5\mu m$ ones (Allen 1968), so is therefore unsuitable for measuring the smaller exhaust particles.

(iii) Laser diffraction technique

Laser diffraction, also known as Low Angle Laser Light Scattering (LALLS), can be used to determine particle size (Rawle 1993). It involves illuminating a suspension of the sample with a laser source and recording the resulting diffraction pattern. A helium-neon laser with a wavelength of $0.63\mu m$ is commonly used and the detector is usually made from a sheet of photosensitive silicon with a number of discrete detection areas. The optimum number of detector areas is between 16 and 32, and their spacing gives rise to the logarithmic nature of the particle size measurement bands. A similar method called photon correlation spectroscopy uses a moving photo multiplier to record the diffraction pattern and is suitable for particles between 1nm and $1\mu m$. The particles are usually suspended in water using a dispersing agent, such as sodium hexametaphosphate. Other fluids can be used if the material reacts with water, such as air or oil. Ultra sound can be applied to the solution to break up conglomerations (loose clumps) of particles, although high intensities may also break up weak particles or agglomerations (fused particle clumps).

The size distribution is calculated from the diffraction pattern using a theoretical model of particle scattering, such as Mie theory. It assumes that the particles are spherical (with a known refractive index) and calculates the volume of particles in each size range required to form the recorded diffraction pattern. The reported sizes are therefore based on spherical particles with the equivalent diffractive properties. The main advantages of this technique is that it is repeatable and can measure particles of sub-micron diameter (typically down to $0.05\mu m$).

(iv) Microscopy

Microscopy allows direct examination of the particles, revealing their size, shape and form. The measurement of size from the images is subject to error caused by having to choose a suitable dimension to measure on irregular shaped particles, such as the largest dimension of each particle, or the smallest, or an average of a number of measurements. Sufficient particles must be measured for the result to be statistically representative of the sample, which may be achieved using computerised image analysis, but at present this method can only give an indication of the sizes present.

As well as optical microscopes other imaging microscopes are available that use different wavelengths. The scanning electron microscope (SEM) can view sub-micron particles (a magnification of x 300,000 is possible) and can also give information on the elemental composition of the sample (Brundle 1992). The SEM works by rastering a focused electron beam across the sample and measuring the energy of returning electrons. Displaying the intensities at locations proportional to the rastered position provides an image of the sample. Elements are identified by comparing the energy levels of the detected electrons (measured in electron volts) with a database of energy levels for different elements. The relative amount of each element can be roughly estimated, although there is no way of knowing exactly what chemical compounds are present. It should be noted that this technique analyzes only the surface atoms of each particle and that it is unable to detect elements of low atomic weight (elements lighter than sodium, or boron with more sensitive systems).

(v) X-ray diffraction

X-ray diffraction (XRD) provides information on chemical composition which is required in addition to the elemental information provided by the SEM in order to determine such parameters as density and refractive index (Brundle 1992). Analytical chemistry (reacting the sample with other chemicals) is an alternative, but the quantity of material required was not available. In XRD an X-ray beam is used to illuminate the sample and the resulting X-ray diffraction pattern measured. This is achieved by changing the angle of the input X-ray beam to the sample surface (angle θ) and measuring the intensity of the diffracted X-ray beam at a symmetric position. The intensities are then plotted against the angle between the input and diffracted X-ray beams (2θ). The crystal structures of different compounds have a unique variation of this intensity with angle 2θ, so the compound in a sample can be determined by comparing the measured 2θ values with a database of values for known compounds. Relative amounts of the identified compounds can be inferred from the relative intensities measured. If the material is amorphous (without a crystal structure) the XRD cannot distinguish the compounds due to the lack of crystal structure. This technique is not as sensitive as the SEM, requires larger samples and provides no spatial information, but does provide important additional chemical information.

5.4.3 Implementation of analysis techniques

It was decided that SEM analysis would be used to provide elemental composition, particle shape (ie. images) and an estimate of the particle sizes present in each collected sample. This was performed at Fort Halstead (UK) using a SEM sensitive to atomic weights as low as boron for all samples except that from the Experimental Aluminised Composite motor, where a SEM sensitive down to Sodium was used. It was found that there was little variation between samples from the same motor type, so only a limited number of SEM analyses were performed. Samples that were of sufficient mass were then sent to Malvern Instruments Ltd (Malvern, UK), who measured particle size by laser diffraction using their 'Mastersizer X' instrument. XRD was used to determine the chemical compounds present in the particles, although samples collected at different locations from the same type of motor had to be combined to provide sufficient material for analysis. Similar analysis was also performed on samples of zirconia, silicon carbide and aluminium particles which were typical of those used in the rocket motor propellants.

5.5 The nature of the collected and propellant particles

5.5.1 Outline of analysis

Analysis was performed on the particles collected by the Centriseps and also on some propellant material. Insufficient particles were collected by the in-flow filters for proper analysis. The propellant compositions of the motors can be found in Appendix A (as released by the manufactures) and the collection positions in Figure 5.10. SEM results are presented for each sample type (image and elemental analysis), while the compounds discovered by XRD are quoted, as the tabular output conveys no additional information (eg. Table 5.8). The following terms are used to define average particle diameters determined by laser diffraction;-

D_{43}	=	$\Sigma d^4/\Sigma d^3$	Average particle diameter weighted by volume (or mass).
D_{32}	=	$\Sigma d^3/\Sigma d^2$	Average particle diameter weighted by cross sectional area.
D_{10}	=	$\Sigma d/n$	Average particle diameter with no weighting.

Values derived for all the analyzed samples can be found in Table 5.5, while values typical of each sample type are shown in Table 5.6. The differences in the average particle diameters calculated for samples from the same motor type can be miss-leading, as the presence of a few relatively large particles can change the D_{43} or D_{32} values considerably, while if graphs of particle size distribution are examined trends in distribution can be noted and any anomalies appreciated. The particle size distribution graphs included for each sample often showed one or two dominant particle diameter ranges, which are termed as lobes (Table 5.7).

A limitation was discovered in the size analysis performed by Malvern Instruments Ltd, as shown in Figure 5.25. The result shows a zero volume of small particles (diameters below approximately 1.0μm), but this is purely due to system resolution. The smallest resolvable percentage of the total volume of all the particles present is 0.01% and any quantity below this considered as 0%. Therefore, any particle size whose volume is less than 0.01% will not be reported. This may significantly affect the D_{10} particle diameter, due to the large number of particles this small volume may contain.

5.5.2 Particle analysis results

i) Unfired zirconia powder

The sample of zirconia powder was supplied by the Royal Ordnance and was identical to that used in the manufacture of the Heavyweight motors. Particle size analysis gave a D_{43} of 2.40μm, D_{32} of 1.27μm and D_{10} of 0.26μm. In the SEM image (Figure 5.26) the zirconia has a very jagged appearance similar to crushed granite. This is caused by its crystalline structure and the crushing processes used in its manufacture. The elemental composition reported by the SEM (Figure 5.27) indicates that the 'zirconia' actually contained calcium and hafnium as well as zirconium (the oxygen cannot be detected by SEM). Information obtained from the manufacturers reported that the material was 'lime stabilized zirconia' (calcium oxide had been added during manufacture) and that there were hafnium impurities (commonly found in zirconia ores). However analysis by XRD (Table 5.8) showed that the particles consisted of a mixture of calcium zirconium oxide and zirconium oxide (zirconia).

ii) Unfired silicon carbide powder

This sample was also obtained from the Royal Ordnance and is identical to the material used in the propellant. Particle size analysis (Figure 5.24) showed that the D_{43} was 2.95μm, the D_{32} 1.71μm and the D_{10} 0.18μm. The 'by volume' size distribution was bimodal, with lobes at 0.2μm and 2μm. In the SEM images (Figures 5.28) the silicon carbide particles had sharper edges than the zirconia ones and had the appearance of broken glass. The elemental composition (Figure 5.29) was predominantly silicon and carbon, although a few particles showed traces of traces of chromium, iron, nickel and potassium. XRD analysis confirmed that the sample was mainly silicon carbide, no other compounds being present in sufficient quantities to be recorded.

iii) Unfired aluminium powder

This material was provided by the Aluminium Powder Company Ltd and is typical of that added to aluminised propellants. Analysis showed that the particles were much larger than the zirconia or silicon carbide ones, with D_{43} of 54.39μm, D_{32} of 34.87μm and D_{10} of 2.12μm, and with particles diameters ranging up to 200μm (Figure 5.25). Analysis was limited to above 1.0μm because of system resolution (see section 5.5.1). The SEM picture of the particles (Figure 5.30) showed that the particles were of non-uniform shape, although generally smooth. The only detectable element was aluminium (Figure 5.31). XRD analysis also reported pure aluminium, although an oxide coating may have been too thin to detect.

iv) Cast Double Base motor (Firing 1)

The Centriseps collected sufficient material for analysis at radial positions of 40mm and 280mm. The amounts collected at 160mm and the outer two positions were significantly less (see Table 5.2 and Figure 5.15 for collected weights). No definite conclusions could be drawn as the Centriseps may have malfunctioned because of loose filters, although there appears to be a region of high localised particle concentration 280mm from the plume's centre line. The size analysis graphs (Figure 5.32) for the 40mm and 280mm positions are similar, although more particles in the 10 to 100μm range were collected at 280mm. The averaged diameters for the 40mm position were a D_{43} of 13.51μm, a D_{32} of 1.37μm and a D_{10} of 0.14μm.

SEM analysis showed that the particles have a variety of shapes (see Figure 5.33) and that the majority appeared jagged and crystalline in nature, although a few larger spheres were also present. Elemental analysis by SEM (Figure 5.34) showed that there was calcium and magnesium present, with traces of iron and chlorine, and very small amounts of aluminium and lead (the only metallic element reported to be in the propellant was lead, Appendix A). XRD was not performed as insufficient material was collected.

v) Heavyweight motor - 1 and 2% zirconia (Firings 2,3,4 and 7)

Figures 5.15 and 5.17, and Table 5.2 show the weights of particles collected from these motors. As mentioned in section 5.3.4 the Centriseps may have malfunctioned during collection from the 2% seeded motors. Indeed similar amounts of particles appear to have been caught from the motors with lower seeding levels (ie. 1% of zirconia). However, all the results showed that the 40mm position always collected most particles. There was also some evidence that there was a secondary peak in the amount collected at around 280mm, but because of the small quantities involved this is not conclusive (ie. possible errors in weighing etc).

In some of the size distribution analyses (Figures 5.35 to 5.38) the system resolution was not high enough to accurately measure the particles below 0.1μm, so could give no indication if particles were present. The size distribution of the particles collected at 40mm with 1% seeding (Figures 5.35 and 5.36) and 2% seeding (Figures 5.37 and 5.38) were very similar. The difference in D_{43} values between collections was significant, for example firing 4 (1% seeding) collected particles with a D_{43} of 12.29μm, a D_{32} of 4.57μm and a D_{10} of 0.09μm at the 40mm position, while the corresponding values on firing 3 (2% seeding) were 18.56μm, 4.15μm and 0.09μm. The similarity of the D_{32} and D_{10} values indicates that the difference in D_{43} values was due to the collection of relatively few additional larger particles in firing 3 (particles up to 50μm in diameter were observed). All the samples exhibit a bimodal particle size distribution with lobes at 0.25μm and 4.0μm. However, with the 1% seeded motors at the outer collection positions (280mm) the magnitude of the 4.0μm lode relative to the 0.25μm lobe was greater than at the central positions (40mm). This was not apparent in the particles collected from the 2% seeded plume, although this data was less reliable due to the loose filters in the Centriseps.

The size distributions of the collected particles were found to be different to those of the unfired zirconia (Figure 5.23), with a significant increase in D_{43} and D_{32} values (Table 5.6), indicating that larger particles were present in the plume. The D_{10} could not be compared, as the zirconia analysis was performed with a lower resolution system. The original zirconia peak (by number) at 0.2μm was not evident in the collected samples and the 'by volume' peak at around 1.0μm became a trough. The increase in the size of the collected particles was thought to be due to agglomeration of the zirconia in the extreme temperatures of the plume.

When examined by the SEM (Figure 5.39) the collected particles appeared randomly shaped, each particle appearing to be made up of several zirconia particles (as in Figure 5.26) fused together and having lost their jaggedness due to having become semi-molten. Elementally (Figure 5.40) the sample contained mostly zirconia and calcium with traces of iron, hafnium and potassium. Some of the more spherical particles also contained copper. The relevant propellant constituents (Appendix A) were the lime stabilized zirconia (with hafnium impurities, as in Figure 5.40) and salts of potassium and lead. The propellant will also have contained calcium impurities (as stated in Table 4.1). With the exception of lead, metallic elements in the propellant were detected in the collected particles together with iron, which may have been eroded from the Centrisep. The XRD analysis showed the sample to be predominantly calcium zirconium oxide, while the zirconium oxide (ie. true zirconia) present in the unfired zirconia was not detected.

vi) Heavyweight motor - 2% silicon carbide (Firing 6)

The 40mm position collected the largest amount of particles (see Table 5.2 and Figure 5.18 for collected weights), while the particle size distribution (Figure 5.41) showed there to be diameters ranging from 0.07μm to 100μm, with a lobe (by volume) at 5μm. At the 160mm position the size distribution showed that a greater number of sub-micron particles were collected, resulting in a second lobe at 0.2μm (by volume), while at 280mm more particles of between 10μm and 100μm were present (below 0.4μm the measurement is unreliable due to system resolution). The collection at 160mm was thought to be most representative of plume particles, as the sub-micron particles collected at the 40mm position may have agglomerated after collection (due to the higher temperature) and particle sizes were not reported below 0.4μm in the 280mm sample. Typical diameter values at 180mm were a D_{43} of 27.33μm, a D_{32} of 4.74μm and a D_{10} of 0.09μm, which are substantially larger than the unfired silicon carbide values (the D_{10} should not be directly compared due changes in system resolution).

The SEM analysis (Figures 5.43) showed that the particles were less jagged than the unfired silicon carbide (Figure 5.28) and appeared to have agglomerated. The elemental analysis (Figure 5.44) showed that silicon, carbon and zirconium were present, although the zirconium was due to contamination of the Centriseps by the previous firings of zirconia seeded motors. The XRD reported silicon carbide and small quantities of calcium zirconium oxide, again due to contamination from the previous firings.

vii) Heavyweight motor - unseeded (Firing 5)

The greatest amount of material was collected at the 40mm position (Figure 5.19) and the size analysis (Figure 5.42) showed a bimodal distribution (by volume), with lobes at 0.3μm and 4.5μm. This was similar to the zirconia seeded motor samples (Figures 5.35 to 5.38) except that the number of particles collected between 0.1μm and 0.9μm was higher. The diameter values (40mm position) were a D_{43} of 24.20μm, a D_{32} of 2.20μm and a D_{10} of 0.19μm. At the 160mm position the larger lobe of the bimodal distribution (4.5μm) tended towards the smaller diameters, which resulted in smaller averaged diameter values.

Under the SEM (Figure 5.45) the particles were similar in appearance to the zirconia particles collected during previous firings (Figure 5.39) and were therefore mostly contaminates from the previous firing of a zirconia seeded motor. Elemental analysis also reported that zirconium was present (Figure 5.42). It was concluded that the majority of particles in this sample were from the previous firings (due to contamination). Therefore any differences in the particle size distribution of the samples collected from the unseeded and the zirconia seeded motors were important as they were due to material other than that used for seeding. The main difference was the greater number of particles in the 0.1 to 0.9μm diameter range, which must therefore have been produced by the unseeded motor.

viii) Experimental Aluminised Composite motor (proving trial)

The size distribution was only obtained for particles collected on the centre line position at 5.14m behind the motor (Figure 5.47). A bimodal size distribution (by volume) was apparent, with lobes at 0.3μm and 5.0μm. The particle average diameters were a D_{43} of 5.61μm, a D_{32} of 2.19μm and a D_{10} of 0.20μm, although when comparing these sizes with those from other collections it should be noted that the system was of lower resolution (ie. particles below 0.1μm were not measured). Under the SEM the particles were almost all spherical (Figures 5.48), with only a few irregular shaped particles, as opposed to the predominantly non-uniform aluminium powder (Figure 5.30). Only aluminium was detected by SEM (XRD was not performed) and was the only metallic element reported to be in the propellant (Appendix A).

ix) CRV7 C14 - aluminised composite (Firings 10, 11 and 13)

Figure 5.21 and Table 5.3 show the sample weights collected across the plume at 1.5 and 2.5m from the nozzle. There was variation in the sample weights from the two 2.5m collections, although generally more particles were collected further away from the centre of the plume than at the 1.5m position. There was a bimodal size distribution (by volume) in all of the particle samples (Figures 5.49 to 5.51), with lobes at 0.2μm and 3.0μm. At 2.5m from the nozzle the magnitude of the 3.0μm lobe became larger at collection positions further from the centre line. Averaged particle diameters for the 80mm position (2.5m from the nozzle, Figure 5.51) were a D_{43} of 12.28μm, a D_{32} of

$1.11\mu m$ and a D_{10} of $0.11\mu m$.

SEM images (Figure 5.52) showed that the particles were predominantly spherical, although there were a small number of irregularly shaped particles and conglomerates. Their shape had therefore changed from the non-uniform one of unfired aluminium powder particles (Figure 5.30). Aluminium was the major element, with traces of oxygen, silicon, iron, calcium, potassium and chlorine (Figure 5.53). Separate analysis of the irregular shaped particles showed that they had higher concentrations of some of these traces and one particle contained zirconia, copper and chromium. The propellant was known to contain ammonium perchlorate, aluminium, ferric oxide and a calcium salt (Appendix A), and elements from these were observed in the collected samples. XRD analysis showed that the sample was mostly aluminium oxide and that this occurred in alpha (corundum) and beta crystal structures.

x) CRV7 C15 - non-aluminised composite (Firings 8, 9 and 12)

Figure 5.22 shows the weights collected at different radial distances 1.5 and 2.5m downstream from the nozzle. The results seemed fairly consistent, except for one point (2.5m, 160mm) where it was believed that particles had been lost during handling of the sample. At the 1.5m position the most central Centrisep (160mm) collected relatively few particles and it was believed that most of the particles must have inhabited a more central unmeasured region. The size distribution graphs (Figures 5.54 to 5.56) showed a bimodal distribution (by volume) very similar to the C14, although the analyses were subject to error due limitations in system resolution (as mentioned in section 5.5.2). The averaged diameters for the 80mm (2.5m) sample were a D_{43} of $9.54\mu m$, a D_{32} of $1.54\mu m$ and a D_{10} of $0.11\mu m$ (the other samples sizes appear in Table 5.5).

SEM analysis (Figures 5.57) showed the particles consisted of spheres and irregular shaped particles and the main elements detected were aluminium (none was contained in the propellant, but other motor parts did contain aluminium, Appendix A) and silicon, with minor quantities of calcium, chromium, zirconia, iron, copper and potassium (Figure 5.58). Further analysis showed that the spheres were mostly aluminium and/or silicon, while the irregular shaped particles contained higher levels of the other elements quoted above. The relevant propellant constituents were zirconium silicate, ferric oxide and a calcium salt.

The XRD results showed that the sample was made up of calcium zirconium oxide, silicon oxide and alumina (delta form crystal structure, different to that collected from the C14). There was also a large amorphous content (material that does not have a recognisable crystal structure), which could be various plastics or rare compounds. Although alumina was detected in the exhaust particles the propellant composition (Appendix A) included no aluminium. However, aluminum foil was used to wrap the propellant charge and alumina cement was used during motor construction. This explains the differences in alumina crystal structure and particle shape compared with the aluminised C14 motor.

5.5.3 Discussion of particle behaviour

In general most of the particles were collected in the centre of the plume, with a rapid drop in concentration moving towards the outer edges where only small numbers of particles were present. There were also some localised concentrations of particles, but these could not be properly determined using the present data. A correlation between particle size distribution and radial position could not be obtained, although larger particle sizes were more abundant further away from the centre of the plume in a majority of measurements (eg. the C14 in Figure 5.50).

The general shape of the size distributions are expressed as 'lobes' in Table 5.7 (ie. where there was a major peak or a group of smaller peaks) and it can be seen that all the exhaust particles had a lobe at below 0.3μm in their 'by volume' size distributions. As mentioned in section 5.5.2(vii) the particles collected from the unseeded Heavyweight motor were dominated by particles of this size range, which indicates that they were the basic exhaust particles produced by the motor (ie. from nozzle erosion etc and propellant constituents other than the refractory seeding). All the exhaust samples exhibited a second larger lobe at 3-6μm, but there was no correlation between the position of this lobe and the propellant or seeding material. Instead there appeared to be a relationship between motor case type (or a connected constraint) and the particle size at the centre of this larger lobe. The CDB, C14 and C15 motors, which are all ex-military service, all exhibited a lobe at 3.0-3.6μm, while the Heavyweight and the Experimental Aluminised Composite motors (all manufactured by the Royal Ordnance using heavyweight type casings) showed a lobe at 4.2-6.0μm. The 'by number' size distributions were all dominated by particles of approximately 0.1μm diameter, although this was composed of very little particle mass.

In section 4.4.2 particle sizes suggested by other researchers were reviewed. For motors with aluminised composites propellants D_{43} diameters of between 5.23μm and 7.0μm were reported, compared with a D_{43} of between 3.38μm and 15.12μm collected from the C14's plume (up to 280mm from the plume centre) and a D_{43} of 5.6μm from the Experimental Aluminised Composite's plume. The corresponding reported D_{10} was 0.2μm, compared with the C14 and Experimental Aluminised Composite values of 0.1μm and 0.2μm respectively. Traineau (1992) reported a bimodal size distribution (by volume) for aluminised composite motors, with lobes at 1μm and 6μm, while the bimodal distribution seen with the Experimental Aluminised Composite and C14 motors were based around smaller lobe sizes (0.3μm and 5.0μm, and 0.2μm and 3.0μm respectively). The differences in these values could have been due to differences in collection and analysis methods, or due to differences in the design of the rocket motor (full details were not given in the references). JANNAF 1977 stated that aluminised motors produced carbon particles with diameters of between 0.02μm and 0.08μm in addition to the alumina ones. Particles in this sizes range were also collected during the present research, but the chemical consistency could not be established because the mass of particles was insufficient for analysis.

The chemical compositions of the collected samples, discovered by SEM and XRD, were directly related to the motor's propellant and the materials used in its construction (Appendix A). With aluminised propellants the aluminium (Figure 5.30) had oxidised to form alumina particles, which were spherical (Figure 5.48) due to a liquid phase during their formation. Particles collected from motors whose propellants contained lime stabilised zirconia or silicon carbide were more irregular in shape (Figures 5.39 and 5.43). The original particles in the propellant (Figures 5.26 and 5.28) appeared to have become only semi-molten in the plume (their melting points are higher than aluminium's), which caused them to lose their sharp corners and to become fused together. Although most of the minor elements in the collected sample were identified in the motor, the origins of some were never identified (for example magnesium in the CDB motor and copper and chromium in the CRV7 C14). More precise details of the propellant constituents and motor constructional materials would be required if the origins of all the various elements detected in the collected material were to be established, although contamination from other sources cannot be discounted, for example material entrained into the plume from the firing bay.

Literature on alumina particle chemical composition was reported in section 4.4.3. The alpha and gamma phase crystal structures of the alumina particles reported by Oliver (1992) were measured in the Experimental Aluminised Composite and C14 samples using the XRD analysis, although the C15 produced delta phase alumina from the aluminium and alumina used in the motor construction. The formation of a chloride layer on the surface of alumina particles caused by the chlorine content of composite propellants was reported by Cofer (1978), but this layer was not identified in the samples analyzed by XRD (the quantities of chloride may have been too small), although some chlorine was detected by the SEM. Information about particles from non-aluminised or double base motors was not discovered in the literature searches.

5.6 Conclusions and recommendations for particle characterisation

5.6.1 Conclusions

Techniques for particle collection were successfully developed and demonstrated on rocket exhaust plumes. The collected particles were undamaged and collected in sufficient quantities by the Centriseps to allow full analysis. In some cases more particles could have been collected if a larger capacity had been incorporated into the Centriseps' filter holders. The in-flow filter technique was less successful and collected too few particles for proper analysis. Particle size, shape and chemical constituency were determined by scanning electron microscopy, X-ray diffraction and laser diffraction for samples collected from a number of different types of rocket motor.

The chemical composition of the collected plume particles was directly related to the propellant composition and the materials used in the motor's construction, although the origins of a number of trace elements in the particles could not be identified. Aluminium present in the propellant formed near spherical alumina particles, while refractory materials (zirconia or silicon carbide) became semi molten in the plume and formed into clusters. Other elements may have also coated the particles or react with them. There was no clear correlation between the particle sizes in the propellant and the particle sizes collected, although a particle shape was dependent on its constituents. A majority of the plume particles were present in a central core region of the plume which was surrounded by a region of lower concentration. The particle size distribution appeared to tend towards larger particles away from the centre of the plume and there may have been some localised regions of higher particle concentration. As a rough guide the average particle has a diameter of approximately $0.1\mu m$ (by number) and an average 'by volume' of $10\mu m$.

5.5.2 Recommendations

In order to improve the collection and analysis techniques the following are recommended;-

i) Increase the collection capacity behind the filter in the Centrisep.
ii) Increase the operational temperature of the Centriseps.
iii) Improve analysis below $0.5\mu m$ (improved laser diffraction systems).
iv) Concentrate the sub-micron particles in the samples (for example by sieving out the larger particles) so that the chemical composition can be determined by SEM or XRD.
v) Investigate the use of non intrusive techniques.

Additional motor firings are required to measure the following;-

i) The variation of particle characteristics in different regions of the plume.
ii) The effect of changing motor variables on particle characteristics (ie. thrust, combustion chamber residence time, temperature, propellant, particle levels and types etc).

6 PLUME PARTICLE VELOCITY MEASUREMENT

6.1 Review of anemometry techniques

6.1.1 Introduction

Measurements of rocket exhaust plume flow field variables are required for the development and validation of plume prediction codes. Techniques are available for the measurement of the gas phase, but results are often inconclusive, with poor spatial resolution or ambiguity in the variable being measured. An example is the measurement of plume gas temperature using Coherent Anti-Stokes Raman Spectroscopy (Williams 1992). The measurement of exhaust plume particles is not only important for the development of two phase plume prediction codes, but also for single phase codes, as gas variables can be estimated from changes in the particle values (eg. particle acceleration infers that the gas velocity is higher than the particle velocity).

There are a number of techniques available for measuring particle velocities, the main reason for their development being the assumption that the particle velocity is representative of the gas phase. This is only true if the particles are relatively small and velocity gradients are moderate, which is not the case in rocket plumes. The underlying principles of several of these measurement techniques restricts them to lower velocities (< 1000m/s), although technological advances may increase this limit in the future (eg. increased imaging rates or improved data acquisition). Other techniques are inherently more suitable for high velocity measurement as they measure the Doppler shift of light scattered by the particles, which is larger at higher velocities. Systems that offer good spatial resolution and accuracy can be assembled from commercially available parts. However, there has been little previous work using such systems in the hostile environment of rocket exhausts plumes and therefore the suitability of each method had to be assessed to ensure that the most appropriate technique was implemented.

6.1.2 Interference pattern technique

This technique is most often called Laser Doppler Anemometry (LDA), or more correctly differential or fringe LDA and involves the over lapping of two coherent laser beams to form an interference or fringe pattern (consisting of regions of constructive and destructive interference). The regions of constructive interference (ie. high light intensity) are at predetermined distances apart, the distance depending on the light's frequency and the angle between the laser beams. Particles passing through these bright regions produce pulses of scattered light, which are recorded by a suitable detector. The particle velocity is then calculated from the frequency of these pulses and the distance between fringes.

Systems using this technique are commercially available from a number of manufacturers, but are restricted to velocities below approximately 300m/s due to limitations in pulse detection and processing (Dantec 1991). High particle concentrations can also produce unacceptable pulse frequencies and may cause obscuration. Farmer (1978) describes the measurement of rocket exhaust particles, although only on collected particles entrained in an inert flow. The technique has also been established in combusting flows, as demonstrated by Atakan (1981) which describes a series of experiments measuring the burning of aluminium and titanium particles in flames. Systems have also been developed that record velocity and particle size simultaneously (see section 5.1.3). Although this technique is presently unsuitable because of the velocity limitation this may be removed by improvements in technology.

6.1.3 Laser transit anemometers

In laser transit anemometry two parallel laser beams are focused within the measurement volume, with a predetermined distance between them. Particles entering or leaving the volume produce pulses of light as they pass through the beams (or optical 'gates'). These pulses are recorded by a detector and then used by a signal processor to calculate particle velocity (provided the particle concentration is low enough to prevent excessive pulse frequency or obscuration). Higher velocities can be measured by increasing the distance between the two laser beams to maintain a measurable pulse frequency, although the measurement volume may become too large. This method may be useable for measuring lower plume velocities (up to 1000m/s), but cannot measure the higher velocities expected near the nozzle (over 2000m/s).

6.1.4 True Doppler techniques

At velocities typical of the exhaust plume (up to approximately 2000m/s) the Doppler shift of light scattered by particles is relatively large and can be measured by a number of techniques.

The Michelson Interferometer technique uses the light scattered by particles to form a frequency dependent interference pattern. In this system a feedback method is used to maintain the pattern whenever a change in frequency occurs (due to a Doppler shift) and the frequency shift calculated from the feedback voltage required. This technique was used for plume measurement by the author and is described in full in section 6.2.2. Previously this technique had been successfully used to measure particle velocities in the hostile environment of gun muzzles and had recorded velocities of over 2000m/s (Yule 1985).

The Fabry-Perot technique measures the Doppler shift by using a scanning mirror assembly to direct the scattered light on to a detector. The detector output is frequency dependent and by using Fourier analysis the frequencies present can be revealed. James (1966) describes such a system used for measuring alumina and aluminium particles in a nitrogen flow expanded through a nozzle and Morse (1968) describes the measurement of real rocket exhaust plumes (27kN and 2.7kN thrust motors) by this technique. However, the scanning mirror assembly would be prone to miss-alignment by vibration from the rocket motor and the data rate would be relatively slow.

Global Doppler Velocimetry can simultaneously measure particle velocities over a region of flow field (IMechE 1992 and IMechE 1994). The technique operates by illuminating the particles with a laser light sheet and recording two images of the scattered light using a photographic or CCD camera. The light used for one image is passed through a cell with a frequency dependent transmission factor (commonly iodine gas). By comparing the light intensities of both images the frequency shift can be determined and from this the velocity. If image acquisition is fast enough single particle velocities are measured, if not the result is time averaged over the duration of the image acquisition. At present the technique is not developed sufficiently for rocket plume measurement, although it may prove to be an ideal technique.

6.1.5 Particle image velocimetry

A laser sheet is used to illuminate the particles in a flow field while two images are acquired using a photographic or CCD camera. The time interval between images must be very small so that the same particles are imaged twice. Image analysis software calculates the particle velocities by locating the same particle in both images and measuring the distance travelled. Particle concentrations must be low enough to prevent obscuration or over population which would hinder analysis. At higher velocities the particle images become distorted and particles travel too far between images for analysis to be carried out. Many systems are available from suppliers such as TSI, Dantec and Oxford Lasers. By using holographic imaging it is possible to instantaneously measure all three components of velocity throughout the measurement region (Holo-Cinematographic velocimetry, HCV). More information can be found in IMechE (1992) and IMechE (1994).

Typically this technique is limited by image acquisition to velocities below those of interest in the plume, although this limitation can be partially removed by using two laser pulses to illuminate the particles twice on the same image. Suitable systems for use on the exhaust plume could not be identified.

6.2 The Michelson interferometer anemometer

6.2.1 Reasons for selection

Because of the complexity of anemometry systems their purchase or rental costs are extremely high. A Michelson interferometer was located within the DRA which was available for this research. As well as this important financial reason there were also substantial technical reasons for using this technique.

This technique offered the possibility of accurately measuring high velocity two phase flows using a relatively small measurement volume and with a high data rate (~ 1kHz). The system was suited to high velocity measurements in hostile environments as it had previously been used to measure particle velocities of over 2000m/s in gun barrels and this had been documented (Yule 1984 and Yule 1985). The possibility of major damage to the system was small, as long optical fibres allowed the main components of the system to be positioned well away from the rocket motor. In addition to the basic equipment only standard optical components were required to illuminate the measurement volume with the laser and to direct the scattered light into the detection fibre. There was the possibility of optical miss-alignment, but this could be minimised by illuminating sufficient plume with the laser beam.

It was concluded that the system was suitable for plume measurements providing enough scattered light reached the detector optics relative to the background levels. This depended on preventing optical miss-alignment during the firing (possibly due to the distortion of the laser beams by gas density gradients), obscuration because of high particle concentration, too few particles present to scatter enough light and plume emissions in the same waveband as the laser or scattered light.

6.2.2 Principles of operation

The anemometer measured the Doppler shift of light scattered by particles passing through a region illuminated by a 4 Watt Argon ion laser configured with a intra cavity etalon to produce light of a very narrow band width . The scattered light was collected and passed into a Michelson interferometer (manufactured by Diehl GmBh, Germany) where the light was divided into two (Figure 6.1). One half of the light passed through a glass block to give a wavelength dependent path difference, while the other half passed through a Pockel cell whose optical path length was controlled by an input voltage. The light beams were then recombined to form an interference pattern. Detectors were located on two light fringes, so that any changes in fringe pattern could be detected (due to a change in frequency and the effect of the glass block). The detector voltages were then processed to produce a feedback voltage to control the Pockel cell, causing its path length to alter, returning the fringes to their original locations. The voltage required for this was proportional to the change in frequency during the experiment (the Doppler shift), which was in turn related to particle velocity.

The relationship between feedback voltage and frequency change was determined by recording the change in feedback voltage whilst altering the laser frequency by changing the temperature of the intra cavity etalon to mode hop the laser. Each hop produced a 149.9MHz change in frequency and provided a reliable method for interferometer calibration. The relationship between velocity and measured frequency was determined by Doppler theory. This states that for a observer on a moving object (ie. the particle) there is an apparent frequency change to any radiation directed at him proportional to the ratio of his velocity in the direction of the radiation and the velocity of the radiation. The change in frequency is expressed mathematically below;-

$$d(freq_1) = freq\frac{v}{c}\cos\alpha$$

Eqn 6.1

Where;-

v is the particle velocity.

c is the velocity of light.

α is the angle between the beam of light and the particles direction of movement.
(freq) is the laser frequency.

This is also true for a stationary observer viewing light emitted by a moving object. With the system under discussion the emitter and the detector were both stationary, but the light was reflected (or scattered) by moving particles. The particles at first acted as observers and then as emitters, so two Doppler shifts occurred. Therefore the expression for the second frequency change is;-

$$d(freq_2)=(freq+d(freq_1))\frac{v}{c}\cos\beta=(freq+freq\frac{v}{c}\cos\alpha)\frac{v}{c}\cos\beta$$

Eqn 6.2

As $(v/c)^2$ tends to zero this becomes;-

$$d(freq_2)=freq\frac{v}{c}\cos\beta$$

Eqn 6.3

The total frequency shift becomes;-

$$d(freq_{total})=d(freq_1)+d(freq_2)=freq\frac{v}{c}(\cos\alpha+\cos\beta)$$

Eqn 6.4

Therefore if the initial laser frequency and the illumination and detection angles are known the velocity can be calculated from the measured frequency change (ie. the feedback voltage supplied to the Pockel cell). The system's accuracy partly depended on the accuracy of voltage and angle measurement. Allowing for reasonable error in each of these the total error that they introduced was estimated to be less than five percent (including the initial errors in calibration).

6.2.3 Optical arrangement

A modified optical arrangement was required to make the anemometer suitable for plume measurement (Figure 6.2). The main factors that had to be considered were;- the optics needed to be robust, the laser and interferometer were to be up 30 metres from the plume, a 35cm gap was required between lenses and the plume, and the focusing of the laser light and collection of the scattered light needed to be as efficient as possible. A 100/140μm diameter fibre was used to link the laser to the delivery optics, which consisted of a 40mm diameter lens (f=65mm) mounted on an optical rail. This formed a 450μm diameter illuminated volume. The collection optics consisted of a 100mm diameter lens (f=160mm) focusing the collected light on to a 200μm PCS fibre. A larger lens would have collected more light, but would not efficiently guide it into the fibre and may have suffered from vibration or buffeting. This arrangement meant collection occurred over a 200μm diameter volume. Measurements were taken where the 450μm diameter illuminated volume and the 200μm diameter collection volume coincided. With 45° geometry this gave a measurement volume of 200μm diameter and 450μm long. As the illuminated region was wider, a misalignment of 100μm was allowable before signal loss.

6.3 Initial plume particle velocity trial

6.3.1 Aims of the trial

The main aims were to establish this system as a technique for measuring plume particle velocities, to gain experience in its operation and find out any limitations. As plume measurements had not previously been made it was decided to use plumes containing different particle types and concentrations. Heavyweight motors were used (a generic term for reusable research motors), with a double base propellant, seeded with zirconia or silicon carbide particles and a flame suppressant added to the propellant to reduce plume emissions. It was hoped that at least one firing would allow sufficient laser light to pass through the plume, be scattered by the particles, pass back out of the plume and reach the detector optics. If more than one type of plume was found to be measurable then the velocities could be compared. An unseeded motor (ie. no additional particles) was also used to see if there might be enough reflection from density variations in the flow (ie. due to turbulence) or any remaining particles. Before the more expensive Heavyweight motors were used a Cast Double Base motor (CDB- an ex-military service missile motor) was fired to allow the experimenters to gain operational experience. Particle collection also took place on this trial and is reported in Chapter 5 (a firing schedule appears in section 5.3). Norris (1994) describes these anemometer measurements in full.

6.3.2 Experimental set up

The trial took place at J Site, Royal Ordnance Westcott in a semi-enclosed firing bay with the rocket exhausting through the open end. The bay was backed by a disused control room where the interferometer and laser were positioned, with the fibre optics fed through the dividing blast wall (Figure 6.3). The voltage output by the interferometer (ie. the measured velocity) was recorded using a PC based acquisition system and a digital storage scope, which also recorded the photomultiplier tube voltages and the pulse used to ignite the motor. The interferometer output voltage was expected to vary from 0-1.5 volts, corresponding to a 2.25GHz frequency shift which allowed velocities up to 600m/s to be measured before the system reset itself (45^0 geometry). If required the system could be re-configured to measure higher velocities. The optical arrangements at the ends of the optical fibres were mounted either side of the rocket motor on a heavy steel table bolted to the floor of the bay (Figure 6.4). A microscope slide was held in a small optical support to provide a target for the laser and for setting the anemometer's zero reference velocity.

6.3.3 The firings

The term 'indicated velocity' was used to describe the velocity value calculated from the feedback voltage, but they were not real velocities (see section 6.3.4). All measurements were made on the centre line 185mm from the nozzle, except for Firing 7 where the distance was increased to 300mm. Photo multiplier tube (PMT) output voltage graphs are not included because of the low quality of the digital scope output, although relevant information is quoted in the text. Thrust curves for these motors appear in Appendix A.

Firing 1, CDB motor

On ignition a negative indicated velocity was briefly recorded, followed by 5 seconds of apparent velocity measurement (Figure 6.5). The indicated velocity varied from 275m/s to 350m/s and the signal was lost when the boost phase of the motor ended (the high thrust phase) and the sustain phase began (the low thrust phase). The PMT voltages were initially 6V with the stationary target, dropping to the background level (4V) as the target blew away. As the plume appeared the PMT voltages rose to 7V and dropped to the background level at the end of the boost phase. There was therefore some correlation between the PMT voltages and the presence of the boost phase plume.

A video was also made of the laser light hitting the screen used to prevent the escape of laser light. This showed that the path of the laser was not significantly deflected or attenuated by the plume. A photograph of a CDB firing appears as Figure 6.13.

Firing 2, Heavyweight motor seeded with 2% zirconia

The initial spike in indicated velocity (Figure 6.6) was caused by the motor's igniter and was followed by a steady reading of 490m/s for the duration of the firing (6.5 seconds). The PMT voltages increased during the firing and diverged from their common value as the thrust subsided.

Firing 3, Heavyweight motor seeded with 2% zirconia

The indicated velocity from this firing (Figure 6.7) was nearly identical to the previous firing of a 2% motor (firing 2), with only a 2% difference. The PMT voltages were also similar.

Firing 4, Heavyweight motor seeded with 1% zirconia

A lower signal level was expected, due to the reduction in scattering material, so the PMT's were made more sensitivity by increasing their supply voltages. This time the indicated velocity rose from 600m/s to 650m/s during the firing (Figure 6.8) and was approximately 20% higher than the 2% zirconia case (firing 2). The thrust was slightly higher than the previous 1% zirconia case (firing 3), which may have caused higher velocities, although the PMT voltages were similar. Photographs were taken during the firing (Figure 6.14).

Firing 5, Heavyweight motor with 0% seeding

The supply voltages to the PMTs were increased as lower signal levels were expected due to the lack of added scattering material. An indicated velocity of 425m/s was measured during the firing with increased noise levels (Figure 6.9). The PMT voltages, however, were barely above the background level during the firing. After the firing an experiment was carried out to see if this indicated velocity was due to low levels of scattered laser light (indicated by the low PMT voltages). A static target was used to reflect laser light into the detector optics and a neutral density filter was place in front of the laser optics (ie. recreating the firing PMT voltages). The anemometer reported an indicated velocity of 450m/s, so it was concluded that the indicated velocity during the firing was due to the low level of scattered light and not due to particle velocity. From the photographs taken during the firing it can be seen that the plume visible emissions were also lower than in firing 4 (Figure 6.15).

Firing 6, Heavyweight motor seeded with 2% silicon carbide

The PMT supply voltages were returned to the levels used for the 1% zirconia firing, as it was anticipated that the silicon carbide would scatter less light because of its darker colour. The indicated velocity (Figure 6.10) was similar to that seen with the zirconia seeding, although smoother and with random negative excursions. The measurement, however, was invalid as the PMT voltages were at saturation level (8V) throughout the firing. In a video and photographs of the firing (Figure 6.16) it was quite noticeable that this firing was much brighter than the previous ones. The emission levels of the plume were therefore too high for the detectors to operate.

Firing 7, Heavyweight motor seeded with 1% zirconia

The measurement position was 115mm further downstream for this firing. The indicated velocity (Figure 6.11) was very similar to the previous 1% zirconia firing, but with an indicated velocity of around 500m/s, 17% lower. The PMT monitoring voltages were similar to those in firing 3.

6.3.4 Discussion of the results

Firstly it should be noted that the anemometer system operated in the exhaust plume environment and the optics adjacent to the plume were not damaged, indicating the robustness of the system. Originally it appeared that good velocity measurements were made on the plumes produced by the 1 and 2% zirconia seeded motors and the boost phase of the CDB motor, although their accuracy and validity was unproven (the last paragraph of this section elaborates why these results were invalid). During the firing of the silicon carbide seeded motor the interferometer was unable to operate as the PMTs saturated. Conversely during the firing of the 0% seeded motor the PMT voltages were barely above the background level and it was found that the indicated velocity was purely due to the low levels of scattered light. Seeding with zirconia appeared to produce enough scattered light for the interferometer to operate without causing excessive plume emissions. Recording the PMT voltages proved to be invaluable in deciding if the measurements were of particle velocities and not due to system limitations.

The indicated velocities were very stable during the firings and were reproducible between firings with the same experimental parameters (eg. firings 2 and 3). Because of this it was believed that plume particle velocity profiles could be created by measuring several positions during one or more firings. Decreasing the seeding levels (ie. firings 3 and 4) appeared to cause the indicated velocity to increase by 20%, but it was decided that without knowledge of the velocity gradients present in the plume the difference in indicated velocity might be due to small changes in measurement position. There was a drop in indicated velocity when the measurement position was moved further downstream (firings 4 and 7), but again without greater knowledge of the flow field it was not known if this drop was representative.

Although the system was calibrated in terms of frequency measurement, the relationship between frequency shift and velocity had not been experimentally proven. There was also some disagreement over the equation used to derive the velocity, ie. whether only one Doppler shift occurred rather than the two previously described. Further work was also required to study the effect of increased background light levels or reduced signal intensity and how this could be judged by monitoring the PMT output voltages. Being able to stand next to the system while performing measurements was not possible during the rocket firings, but by using a controlled high speed flow this may be possible and would allow adjustments to be made during the measurements. Measurements could also be made over much longer periods.

Using the information gained in subsequent trials (see section 6.5) the measurements taken in this trial proved to be invalid. In section 6.4.3 (iv) it is stated that 'if the background light level dominates (over the scattered light) the interferometer output voltage showed the maximum value, regardless of velocity present'. On reviewing the above results it was observed that in all the cases where it appeared valid measurements were taken the system was in fact reporting the maximum value, ie. the system was indicating 'full scale deflection'. This was caused by the dominance of plume emissions over scattered laser light, therefore preventing the system from measuring a single frequency (ie. the Doppler shift frequency). Variations in the indicated velocities arose from setting different interferometer output voltages with the static target. It had been noted that the indicated velocities appeared very constant during the firings, which seemed unlikely, but no reasons for disproving the measurements could be established at the time, although clearly the anemometer had to be used with extreme caution.

6.3.5 Conclusions from the initial plume particle velocity trial

Although no valid measurements were made during this trial, experience was gained in using the equipment in the rocket exhaust environment and it was recognised that further operation of the system was required before the results could be relied upon. The best way of gaining this experience was clearly to measure a much simpler flow of known velocity, as this would also allow the system's operating parameters to be fully explored. Recording the PMT voltages during the firings proved to be invaluable in the assessment of the results, as the indicated velocity output from the interferometer gave no indication of its validity. It was seen that plume emissions were capable of saturating the PMTs (ie. with silicon carbide seeding) and that if the PMT voltages neared the background levels during the firing then measurements became impossible (ie. the unseeded motor). The zirconia seeded motors appeared to produce a plume with an acceptable balance of scattering and emission, ie. signal to background ratio.

When comparing the indicated velocities from different firings it soon became apparent that a much larger number of measurement points would be required to establish a velocity map of the plume. As the indicated velocities appeared to be very stable it was believed that a velocity profile could be recorded by moving the measurement position during the firing relative to the plume. The apparent reproducibility between firings would also allow plume particle velocity profiles to be created using measurements from different firings.

6.4 Anemometer measurements of the controllable high speed flow

6.4.1 Aims

The background of this work was mentioned in the previous section, the objectives being to prove that the anemometer produced reliable results, to calibrate these results, to increase understanding of its underlying principles of operation and to gain further operating experience. The basic experimental set up is described below, followed by each separate investigation. A full report on the operation of the system is given by Norris (1995).

6.4.2 Experimental set up

Flow measurements were preformed on a jet of air produced by large air compressor in Test House 8 at Cranfield University (Figure 6.12). The air was passed through a combustor and a seeding unit before reaching a 38mm diameter nozzle where it was exhausted in to the atmosphere. The combustor burned Kerosene, ignited by a spark plug and could increase the gas temperature to the material limits of the system (around 1000°C). The seeding unit was loaded with titanium oxide particles (D_{43} 0.3μm) and was able to feed the flow at a variable rate. The nozzle was purely a convergent device and the velocity was kept subsonic to prevent the formation of shocks. Velocity measurements were made adjacent to a Pitot tube placed on the centre line of the flow, 60mm down stream from the nozzle. The total (P_T) and static (P_S) pressures from the Pitot were used to determine the Mach number (M) using the following equation;-

$$M^2=\frac{2}{\gamma-1}\,[(\frac{P_T}{P_S})^{\frac{\gamma-1}{\gamma}}-1]$$

Where γ is the ratio of specific heats for air (ie. 1.4) or 'combusted' air (1.33).

To calculate the velocity the Mach number needed to be multiplied by the speed of sound (found in tables using the total temperature measured inside the pipe upstream of the nozzle). The combustor was only used when hot or higher velocity subsonic flows were required and did not cause combustion in the measurement volume.

The same heavy steel table was used to mount the optics as on the previous rocket motor trial. The vibration levels were low enough for the optical benches to be left free standing, allowing easy repositioning. The same fibre optics were used as before, but the data acquisition system was improved so that three channels of data could be recorded, namely the interferometer output and the two PMT monitoring voltages.

6.4.3 The effects of signal intensity and background light

Signal Intensity

A number of experiments were performed in the following manner with the system positioned to measure a static target. Recording of the output voltages was started and then various neutral density filters placed between the laser delivery fibre and its lens. The filters were then removed and the experiment ended. A representative measurement can be found at Figure 6.17. It was discovered during this series of experiments that the interferometer output did not drift significantly with time and there was little noise when a static target was used. Changes in laser light levels affected the interferometer output, but there was no way of predicting these changes, even when PMT voltages were monitored. However, the largest voltage change due to intensity variation corresponded to half that seen when the laser mode hopped, which with 45° geometry corresponded to a 27m/s error. Therefore during a measurement the variation in light intensity levels must be kept to a minimum, for example by using a target that provides a similar light level to that of the plume, but that possible errors in measurement were fairly small.

Background light

This can take the form of broad band light from interior lighting or the sun, or narrow band light from the laser (possibly reflected from nearby surfaces). The former was investigated by measuring a static target and increasing the background light level using a desk lamp. Neutral density filters were then added to reduce the laser light until the interferometer voltage reached the background level (Figure 6.18). Each subsequent filter caused a larger change in interferometer voltage. When the signal level fell below the background level the system could no longer operate and allowed the two PMT voltages to drift apart as it could no longer control the Pockel cell (ie. the laser frequency was not discernable from the background light). Saturation of the PMTs by background or laser light also caused the system to fail.

The effect of narrow band background light was demonstrated using the seeded flow. With the seeding off the laser beam was positioned so that it just touched the front of the Pitot tube. A beam dump was used to ensure that there were no stray reflections of laser light. The seeding was then turned on and the laser beam slowly moved until it no longer struck the Pitot, the scattered light purely coming from the particles. During this the interferometer output changed from zero to the flow velocity value. When light of both frequencies was present the interferometer reported an intermediate result. It is therefore very important to prevent stray laser light from being reflected into the detector optics.

From this section it was concluded that;-

i) The PMTs must not reach saturation levels, ie. a monitor voltage of 7.5V.
ii) For the best result the signal intensity (ie. PMT voltages) must not vary greatly during a measurement.
iii) Stray laser light must be prevented from entering the detector optics.
iv) The signal intensity must be higher than the background level. If the background light level dominates the interferometer output voltage shows the maximum value, regardless of velocity present.
v) The PMT voltages must not differ by more than 5%, as this indicates that the interferometer can no longer control the Pockel cell and that the measurement

is invalid.

6.4.4 Experimental method used for flow measurements

During the investigations described in sections 6.4.5 to 6.4.8 the following experimental procedure was implemented to ensure that the conclusions from section 6.4.3 were adhered to and to alleviate the need to turn the flow off and on between measurements;-

i) Low background light levels were checked by measuring the PMT voltages with the laser off (no seeding).

ii) The optics were positioned so that the measurement volume was just in front of the Pitot, making sure that there was no reflected laser light by monitoring the PMT voltages while turning the laser off and on (no seeding).

iii) The seeding was turned on and the flow measurement recorded.

iv) To record the static reference velocity the laser beam was adjusted to hit the Pitot, without allowing the PMT voltages to saturate and always maintaining a signal to prevent the interferometer drifting. The seeding was then turned off.

v) The seeding was then turned on again and the laser beam moved back to its original position and a second measurement taken of the flow velocity to show that the interferometer had not drifted.

Pitot pressures, flow temperature and pressure in the pipe were monitored throughout the experiment.

6.4.5 The effect of changes in optical geometry

This work had the joint aims of proving that the equation used to describe the Doppler shift was correct (section 6.2.2) and establishing that measurement could be performed over a range of different geometries. A steady velocity of 201.5 +-1 m/s was maintained through out these measurements and the method in section 6.4.4

implemented. Starting with the 45° 45° geometry (used in the initial plume trial) the angles were increased until 127^0 127.5^0 was reached (the angles being measured from the optical-axis of each lens arrangement to the nozzle axis). The intermediate conditions included cases where the angles were not equal (see Table 6.1 and 6.2 for a full set of angles used and the calculated velocities). Measurement was successful at all the angles tried and from analysis of the data it was soon apparent that the equation using two Doppler shifts was correct (Eqn 6.4).

When choosing the geometry it should be noted that the shift measured is proportional to the sum of the cosines of the angles. As the angles approach 0 or 180° the shift will reach its maximum value and therefore inaccuracies or errors in the measurement will be minimised. Conversely if near side on measurements are taken the errors will be maximised. For example if 85° geometry is used a 1° error in angle measurements will cause a 20% error in velocity, but there would only be 2% error at 45° and a 0.2% error at 5°. It has also been assumed that the flow is only in the axial direction. If this is not the case the shift is equivalent to the component of velocity along the bisector of the angle between the beams of light. The value of this component is the product of the velocity and the cosine of the angle between the bisector and the direction of the velocity.

6.4.6 Calibration using the high speed flow

Previously the system had only been calibrated against 'hops' in laser frequency (see section 6.2.2). This was repeated, but measurements were also made with a high speed flow of known velocity. Using the experimental method mentioned in section 6.4.4 measurements were made on flows with velocities of approximately 100, 200, 250 and 300m/s. Figure 6.19 shows a typical result seen during a velocity measurement and Figure 6.20 plots of interferometer output (in counts from the A/D converter) against the various velocities measured by the Pitot. It can be seen that the measurements show a near linear relationship between velocity and counts. The origin has been added as a point, as, although the anemometer cannot operate reliably at low velocities, this was equivalent to a zero velocity case with a static target. The gradient of this graph was 0.728 counts per m/s. The accuracy of the interferometer measurement is to the nearest count and there are possible errors in the velocity measurement with the Pitot (ie. each pressure and temperature measurement may have approximately 1% error). With the additional possibility of the Pitot interfering with the flow, or conversely the Pitot being too far away, it is reasonable to suggest a possible error of +-5% at around 100m/s, possibly dropping as the measured velocity increases.

Figure 6.21 shows the interferometer output when a series of laser mode hops were introduced, each one being equivalent to 149.9MHz. Plotting interferometer output against mode hops (Figure 6.22) gave a gradient of 40.38 counts per mode hop, which equates to 0.740 interferometer counts per 1m/s (using equations number 6.4 in section 6.2.2 and 45^0 geometry), differing by 1.6% with the previous calibration. The accuracy of the calibration by laser mode hops was probably better than +-1% and the difference between calibration methods was well within experimental error.

6.4.7 Measurement of hot flows

Combustion was introduced upstream of the measurement position to see if the anemometer could operate on hot flows and to increase the velocities still higher without reaching supersonic conditions. The results from this experiment can be found in Table 6.3. The velocities were calculated from the interferometer outputs using a conversion factor of 0.73 counts per 1m/s. Although one velocity measured by the anemometer was near to the Pitot value (0.5% away), in both temperature ranges the measured velocities were not repeatable. This was thought not to be due to the increased temperature, but due to the on set of 'roll over' (see section 6.4.8) or unsteady flow effects and was not investigated further during these measurements. It was concluded that high temperatures do not significantly affect the measurement.

6.4.8 Study of the 'roll over' effect

The anemometer output a voltage between 0V and 1.5V to represent the frequency shift it had observed (ie. the change in velocity). It was not known how the system operated when the observed frequency caused the output to exceed this range. During this study an apparent frequency shift was achieved in three different ways. The first two involved measuring a static target and then adjusting the laser frequency (mode hopping) or adjusting the interferometer (ie. changing the optical path difference). The final way was by measuring the high speed flow and reducing the apparent velocity by scattering additional light from a static target (ie. the Pitot tube), but in all cases the effects were the same.

During the investigation the anemometer was set up to measure the frequency shift created by one of the means stated above. The interferometer and PMT voltages were recorded as the frequency shift was increased until rolled over occurred (Figure 6.23). When the interferometer output reached the top of its range it remained at that value as the frequency increased further, until eventually it rolled over. The output did not restart at zero, but instead started at around 0.43V. There was therefore a significant 'dead' range where the system output the same voltage over a range of frequencies. On decreasing the frequency a similar result was observed, this time the output became stuck at 0V and reappeared at 1.2V.

Additional work was carried out after the plume particle velocity profile trial (section 6.5) to establish the exact size of each roll over, ie. the value that must be added to the reported velocities if roll over had occurred. The best way of accurately introducing an apparent frequency shift was found to be by changing the optical path difference in the interferometer. This was achieved by manual adjustment of a micrometer which moved the Wollaston prism inside the interferometer. The anemometer was set up to view a static target and the micrometer position adjusted in steps of 10μm until a roll over occurred. This was repeated twice (Figures 6.23 and 6.24) and the interferometer outputs then plotted against micrometer positions (Figures 6.25 and 6.26). Linear regression was then used to extend the line through the pre-roll over points to above the post-roll over points. The difference between the pre and post roll over results were then measured, and were found to be 1.650+/-0.008V for the first measurement and 1.737+/-0.008V for the second. However, once a correction was made for the slightly different gradient of each graph the values agreed within experimental error, with a final value of 1.72+/-0.02V. In real terms this means that with 45^0 geometry an additional 968m/s must be added to each apparent velocity every time the system rolled over and an additional 1369m/s if 60^0 geometry was used.

6.4.9 Conclusions and recommendations from the high speed flow trial

The anemometer operated successfully on the high speed flow at velocities up to 300m/s and up to 460m/s with elevated temperatures. The equation used to derive the Doppler shift was validated at a wide variety of illumination and detection angles. Calibration of the anemometer using laser mode hops and by using the high speed flow agreed within experimental error. Various operating criteria were discovered that must be complied with if measurements are to be valid, principally that stray narrow band light must be prevented from reaching the detector, the scattered laser light must be above the background level, light levels must not saturate the PMTs and they should not vary greatly during the measurement. Invalid measurement can be determined from the recorded voltages, ie. the PMT voltages should not be saturated or differ by more than 5% (indicating that the interferometer can not maintain the fringe pattern) and if background light dominates the interferometer outputs the maximum voltage.

The accuracy of the system relies on the precision used in the measurement of the optical arrangement, ensuring that the signal intensity is well above background and that the PMT levels are maintained at a reasonable level. If some effort has been made to minimise these then the worst error expected is around 50m/s, plus 3% due to the calibration and geometry (45° geometry). If the PMT voltages meet all the criteria mentioned then the error will be much less, approximately 2m/s plus 2% (at 45°). When the optics are arranged to measure a smaller component of the velocity, ie.

approaching 90^0 to the flow direction, angle measurement becomes more critical to accuracy and the system resolution will decrease (with a corresponding increase in the dynamic range).

Care must be taken to avoid measurements coinciding with the 'dead' range resulting from roll over and if possible roll over should be avoided all together. This can be achieved by setting the output voltage sufficiently low with the static target and if necessary de-sensitising the system by decreasing the size of the glass block used to introduce the optical path difference or by changing the optical geometry (both inherently decrease accuracy).

6.5 Plume particle velocity profile trial

6.5.1 Aims of the trial

The aim of this trial was to measure profiles of particle axial velocities in the plume exhausted by the Heavyweight motors seeded with 2% zirconia, as fired in the initial trial (section 6.3). In this way contours of particle velocity could be constructed for the plume which could then be used for comparison with predictions. Cast Double Base (CDB) motors were used to provide lower cost exhaust plumes during the setting up of the equipment and to hopefully provide comparative measurements.

6.5.2 Experimental set up

The same basic experimental set up was used as in the initial trial (see section 6.3.2), except that the laser and detection optics were moved axially along the plume during the firings to measure velocity profiles (Figure 6.38). A pneumatic system (termed a rodless cylinder) was used that automatically scanned a metal bed along a 2m rail (the stop positions could be varied by movement of the controlling reed switches). A linear potentiometer was used to measure the position of the bed on the rail, the output being recorded by the data acquisition system. Velocities of up to 2m/s could be reached, so a considerable length of plume could be scanned during the 6 second firing of a Heavyweight motor, although during the trial the speed had to be limited to prevent optical miss-alignment due to the high accelerations incurred and the inertia of the lenses. The anemometer optics were bolted to a stiff wooden mounting table fitted onto the metal bed, while the fibre optics were left to trail freely. The control box for operating the rodless cylinder was positioned in the firing control room. After pressing the start button there was a one second delay before the bed travelled to one end of the rodless cylinder. It then stopped momentarily before travelling to the other end and then continued back and forth until the stop button was pressed.

It should be noted that before this trial it was believed that the velocities measured in the initial trial were valid and therefore the interferometer dynamic range was not increased to prevent roll over.

6.5.3 The firings

To differentiate these firings from those carried out during the initial plume trial (section 6.3) 'A' has been added to these firing numbers. Scanning refers to the movement of the optics table. 45° optical geometry was used on all firings except A11 and all measurements were made on the centre line (+/-1°).

Firing A1, CDB motor 1

The measurement position was fixed at 1.6cm from the nozzle. On ignition the PMT's saturated, preventing measurement.

Firing A2, CDB motor 2

To prevent PMT saturation their sensitivity was reduced by decreasing the supply voltages. The measurement position was 18cm from the nozzle for the first 3 seconds after ignition before scanning towards the nozzle began. Although the PMTs were not saturated the interferometer could not control them, ie. the system could not track the scattering frequency and the interferometer output voltage therefore rose to 1.5V (Figure 6.27). The PMT voltages varied as the mechanism scanned and sharply dropped when the motor changed from the boost to the sustain thrust phase (ie. 6 seconds after ignition). This meant that the PMTs were detecting light from the plume, but the ratio of scattered laser light to plume emissions was unknown.

Firing A3, CDB motor 3

To measure the plume emission level firing A2 was repeated, but with the laser turned off. The recorded PMT voltages (Figure 6.28) were very similar to those from firing A2, indicating that plume emissions dominated over any scattered laser light.

On reviewing the data from the initial trial it became apparent that the measurements were invalid because of high plume emissions and that there was no proof that plume measurements were possible (section 6.4.3 experimentally demonstrated the effect of high background levels).

Firing A4, Heavyweight motor 1

It was hoped that more light would be scattered by the additional seeding in these motors and that the plume emissions would be lower due to suppressant additives. It was decided that a record of emission levels should be made first, with the laser off and with the PMTs at their least sensitive. The mechanism was set to remain at 3cm from the nozzle for 3 seconds and then scan downstream. The PMT recorded voltages were near saturation for most of the firing (7V), only dropping to an acceptable level when over 40cm from the nozzle (4V) (Figure 6.29).

It was concluded that useful measurement could only be made if the detected background light was reduced significantly. This was achieved by the addition of a narrow band filter to the detection optics, which transmitted 40% of the light at the laser's frequency (514.5nm) and absorbed 99.9% of light further than 10nm away.

Firing A5, CDB motor 4

To assess the effect of the narrow band filter firing A3 was repeated, again with the laser off. The PMT voltages were greatly reduced (Figure 6.30), remaining below 4V for most of the firing (the level acceptable for measurement), except when 5cm from the nozzle, where they began to rise, hitting 5V. Therefore measurement should be possible in the CDB motor's plume when over 5cm from the nozzle, provided that sufficient scattering of laser light occurred.

Firing A6, CDB motor 5

No data collected due to software error.

Firing A7, CDB motor 6

Using the scanning movement as in firing A2, it was hoped that particle velocity measurements could be made on this firing, but the PMT voltages (Figure 6.31) were only marginally greater than with the laser off (firing A5). It was concluded that the CDB motors had insufficient particles to scatter enough laser light for the interferometer to measure any frequency changes.

Firing A8, Heavyweight motor 2

With the higher seeding levels in the Heavyweight motors it was hoped that the neutral density filter would be more effective. The mechanism was positioned to start at 30cm from the nozzle and then scan to 10cm one second after ignition, stop and then scan downstream. The data collected (Figure 6.32) appeared to meet all the criteria for validity, except between 3.8 and 5 seconds where the PMT voltages differed. At 3.8s the measurement position was stationary, but there may have been momentary variations in particle concentration or plume emission that may have caused PMTs voltages to drift apart. The interferometer output was lower than expected, indicating that roll over may have occurred.

Firing A9, Heavyweight motor 3

The measurement started at 64cm from the nozzle, moving to 4cm after half a second. Once stopped near the nozzle the laser beam was shuttered so that a background was measured as the optics scanned downstream. The PMT voltages (Figure 6.33) were similar between 47 and 22cm from the nozzle, elsewhere the interferometer was unable to control them, allowing them to drift apart. Without the laser there was a significant drop in PMT voltages indicating that there was a good signal to background ratio (ie. scattered light to emitted light).

Firing A10, Heavyweight motor 4

To improve the ability of the interferometer to track the frequency changes the PMT supply voltages were reduced and the measurement position started at 30cm, where there had been previous success. The interferometer initially tracked correctly (Figure 6.34), but as the mechanism scanned towards the nozzle the PMT voltages began to differ, indicating an invalid measurement.

Firing A11, Heavyweight motor 5

Before this firing the ability of the system to maintain tracking (ie. to keep the PMT voltages the same and thereby measure velocity) was investigated by use of a stationary target and interruption of the laser beam. It became apparent that if the interferometer output was adjusted so that it started at 0.9V (with the stationary target) the interferometer was able to regain tracking almost instantaneously and that with the lower voltages previously used tracking was unpredictable. It was assumed that roll over had not occurred in the previous measurements, so to prevent it occurring with the higher initial interferometer voltage the optical geometry was changed to 60° (ie. a smaller component of the axial velocity was measured). The output voltages (Figure 6.35) indicated that a valid measurement was taken throughout the firing, although the interferometer output voltage appeared to have decreased compared to the static target value, indicating a negative velocity or the presence of roll over.

6.5.4 Discussion of the results

The CDB motors proved to be unsuitable for plume measurement because of their low particle level and high emission level. This meant that, even with a narrow band filter, the frequency of light produced by the Doppler shift was not discernable from the background levels. During firings A8 to A11 of the Heavyweights measurements were made which fulfilled all of the criteria for a success mentioned in section 6.4.3. However, there were also periods during firings A8 to A10 when the measurements were invalid due to the PMT voltages deviating (ie. the interferometer could no longer control the Pockel cell correctly). It was found that by starting the interferometer output voltage at a higher value improved the ability of the interferometer to continue operating after breaks in the scattered light. This was implemented in firing A11, resulting in valid measurements throughout the firing.

As well as improved measurement ability in firing A11, the firing also differed in the apparent polarity of the interferometer output compared with firings A8 to A10, ie. the interferometer output during firing A11 indicated a velocity lower than with the static target. As the flow was always positive during the firings, the possibility of a negative velocity was rejected, meaning that either the system's polarity changed between firings (unlikely as no electronic connections had been reversed and only the magnitudes of the optical angles had been changed) or the interferometer output had rolled over, ie. the values reported in section 6.4.8 should be added to the indicated velocities. In the Mini motor trial that followed (section 6.6) it was established that roll over was possible during plume measurement and that polarity remained consistent between firings. Therefore the particle velocities could be calculated assuming 'roll over', but the number of times it had rolled over was not established.

Assuming the particle velocities were similar when measured with different optical geometries (ie. 45^0 and 30^0) only one or two roll overs could have occurred in each case for the calculated velocities to be within reasonable limits, resulting in typical velocities of 1302m/s or 2270m/s for 45^0 geometry and 1254m/s or 2222m/s for 60^0 geometry. The results using both one or two roll overs therefore gave reasonable agreement between the two geometries. The resulting velocities using two roll overs agreed well with the predicted gas velocities (2300m/s at the nozzle dropping to 1700m/s at 50cm). It is a reasonable assumption that gas and particle velocities were similar, especially away from the nozzle (Chapter 7 describes these predictions). The use of two roll overs in the calculation is also supported by previous experimentation (Morse 1968), where particle velocities of approximately 2000 m/s were measured at the exit plane of a rocket motor (aluminised composite propellant). Particle velocities of over 850m/s were measured in the miniature plumes used Mini motor trial (section 6.6) and it would be expected that larger, higher thrust plumes would contain much higher particle velocities. Therefore there is considerable evidence that two roll overs occurred, although this cannot be unequivocally proven from the experimental data recorded during the trial. Performing further measurements of Heavyweight motor plumes with increased interferometer dynamic range would provide such concrete evidence.

Figure 6.37 shows the measured velocities plotted against plume location (two roll overs). Reproducibility between firing was within 14%, although when a second scan was performed in the same firing results differed by up to 10%. The data collected when the measurement position was stationary showed a change in velocity with time (~9%). The particle velocities were therefore changing during the firing, presumably as a result of the propellant or nozzle being burnt away, making comparisons between firings difficult. To obtain a true profile of particle velocities the measurements need to be taken almost simultaneously, ie. the scanning rate of the optics must be very high. Measurements at fixed locations would establish the time dependence of the velocities and may allow the true positional variation to be determined from data recorded at slower scanning rates. The lower particle velocities near to the nozzle (where gas-velocities are highest) were due to particle velocity lags and is discussed further in section 7.3.2.

6.5.5 Conclusions from the plume particle velocity profile trial

The use of a narrow band filter to reduce the detected background light from the plume was vital to the success of this work, resulting in successful measurements of particle velocity along the centre line of the Heavyweight motors plume. Although there was significant evidence that two roll overs had occurred during firings further measurements would be required for conclusive proof. The CDB motors were unsuitable for measurement, although their use was beneficial to the work, allowing the systems limitations to be more fully explored. The scanning mechanism worked well, although the velocities within the plume had a time dependence that must be allowed for when using the velocity profiles. The interferometer's ability to continue operating throughout the firing was found to be considerably enhanced by ensuring that the interferometer output voltage was around 0.9V with the static target.

During any future plume measurements roll over should be avoided, as it introduces uncertainties into the results. This can be achieved by increasing the dynamic range of the anemometer by reducing the size of the glass block in the interferometer (ie. the path difference). Although this would improve system reliability, as it removes the uncertainty due to roll over (ie. how many occurred and the 'dead' range), it also decreases the systems resolution. To compensate the resolution can be increased by amplifying the interferometer output before digital storage, or by using a more accurate means of storage.

6.6 Mini motor trial

6.6.1 Aims of the trial

During the previous trial the limited number of measurements meant that uncertainties remained in the calculation of velocity. The aim of this supplementary trial was to perform measurements with the Michelson anemometer on high speed flows representative of a rocket plume to provide data on the systems roll over characteristics and the consistency of output polarity. Because of limited funding no more Heavyweight motors were available, so the high speed flow was provided by Estes Mini motors (ie. toy rocket motors of low cost). The secondary aim was to assemble a velocity profile so that the Mini motors could be used as velocity references in future research. Norris (1996) reports the work in full.

6.6.2 Method

The same experimental set up was used as in the initial trial (section 6.3.2), except that the optics were mounted on a large wooden board bolted to the floor of the firing bay. A small metal holder was bolted at suitable positions on this board for mounting the Mini motors (Figure 6.39). The board ensured that there was no relative movement between plume and optics, and allowed easy repositioning. Ignition was electrical, by means of a 12V supply and a switch positioned along side the anemometer. A total of 32 Mini motors were fired with various optical arrangements and measurement positions (Table 6.4). The Mini motors used had maximum thrusts of 12N (D type) or 6N (C type) and burnt for just over a second (Appendix A). They also had an 'eject' charge (to launch a recovery parachute) which was delayed by means of a slow burning fuse that produced sufficient smoke to scatter laser light, but had negligible velocity.

6.6.3 Results

Measurement of the particle velocities proved possible with the addition of the narrow band filter to the detection optics. Because of the large number of results only those influential in meeting the aims of the trial are reported here. During all of the 32 firings the polarity of the system remained consistent, reversing only when the optical geometry was reversed. Measurements performed at 45mm from the nozzle showed that there was some variation in the measured velocities between firings, but that such variations were primarily due to differences in motor performance (eg. Figures 6.40 and 6.41), although total impulse appeared to be maintained (ie. thrust multiplied by time). Attempts were then made to demonstrate roll over by increasing the interferometer output corresponding to the static target, but instead the interferometer output remained in the 'dead' region, as insufficiently velocity was present.

It was decided to map out the velocities in the D type motors plume so that the region of highest particle velocity could be found. The resulting plot (Figure 6.42) showed that the best location for achieving roll over was 18mm from the nozzle (Figure 6.43 is the measurement result). The interferometer output voltage corresponding to the static target was again increased so that the measured velocity would hopefully cause the system to roll over. After a number of attempts where the interferometer remained in the 'dead' region (Figure 6.44), roll over eventually occurred on the last two firings of the trial (eg. Figure 6.45). Half a second after ignition the measured velocity avoiding roll over was 650m/s (from Figure 6.43) and with roll over 700m/s (from Figure 6.45), which agreed within the error limits of the experiment. The main source of error was that reproducibility between motors was not consistent, variations of over 30% having been measured.

6.6.4 Conclusions from the Mini motor trial

The polarity of the interferometer remained consistent throughout the trial and the roll over phenomena was experimentally demonstrated on a high speed flow representative of a full size rocket motor. The system proved to be reliable throughout this trial. Particle velocities were measured along the centre line of the Mini motor plumes to provide a reference flow field for future particle velocity measurements, such as with

Doppler Global Anemometry, although reproducibility between firings was poor.

6.7 Conclusions and recommendations for particle velocity measurement

6.7.1 Overview of the data collected

Each stage of the research provided valuable information that contributed to the production of accurate rocket plume velocity measurements. The main findings from each trial are listed below;-

i) Initial plume particle velocity trial (section 6.3).

At the time it was believed particle velocity measurements were made in rocket plumes, but after the subsequent work (section 6.5) these were found to be only system voltages. It was observed that the PMT voltages could be used to judge the validity of the measurements, although it was not known exactly how. The use of fibre optics and lenses adjacent to the plume was established.

ii) High speed flow trials (section 6.4).

These trials used a high speed flow rig at Cranfield University to provide a flow of known velocity for system calibration and improve the operation of the system. Various operating parameters were varied, such as background light and geometry. The 'roll over' phenomena was also examined.

iii) Plume particle velocity profile trial (section 6.5).

It was believed that the system had measured plume particle velocities in the initial trial, so a further trial using rocket motors was attempted, but this time using moving optics to scan the plume. After the first firings it became apparent that velocities were not being measured and that the data from the initial trial was also invalid. By using motors with higher particle seeding levels and by using a narrow band filter, measurements that fulfilled all the requirements for validity were successfully made. There was still ambiguity in the calculation of the velocities, ie. was polarity inconsistent or did roll over occur.

iv) Mini motor trial (section 6.6).

This final trial used Estes Mini motors to provide further measurements to demonstrate that the anemometer's polarity remained consistent and to show that the same velocity was measured when the anemometer was adjusted to prevent roll over and subsequently adjusted to include roll over. The measurements taken in section 6.5 could therefore be confidently converted to velocities making use of the roll over phenomena.

6.7.2 Conclusions

By drawing together all the information from the various trials it is believed that the aims of the research have been met, ie. profiles of particle velocity have been measured in rocket exhaust plumes and their reliability demonstrated. These measurements have already been used in the assessment of plume particle predictions (Chapter 7) and will hopefully provide future code development with a sound base to work from. However, these measurements were not comprehensive, as measurements were only made along the centre line and no attempt was made to measure radial velocities. There may also be significant variation in the particle velocities present in plumes produced by different types of rocket motor (in design and propellant), which would require a parametric study to establish.

The risk involved in future measurements was significantly reduced by improving the understanding and operation of the Michelson interferometer in the rocket exhaust environment, and also by the future use of low cost velocity references to establish measurement techniques (ie. the Estes Mini motors).

6.7.3 Recommendations

For the Michelson interferometer/anemometer

i) Increase the dynamic range of the anemometer to avoid 'roll over' by changing the glass block in the interferometer.

ii) Improve anemometer accuracy by improving the recording electronics (principally the inclusion of an amplifier).

iii) Strengthen the optics so that the scanning mechanism can be used at full speed.

For future measurements

i) Assess other anemometer systems now available offering whole field measurement and/or particle size data (principally Doppler Global Anemometry and advanced PIV). Estes Mini motors can be used in this process.

ii) Further measurements be made on the zirconia seeded Heavyweight motors to construct a particle velocity contour map, using the Michelson anemometer or a replacement from (i). This would also remove any doubt over the number of roll overs used in the present calculations.

iii) Measurements be made on Heavyweight motors seeded with different sizes or types of particle to determine their effect on plume particle velocity.

iv) Measurements be made on other types of motor to demonstrate the effect of different propellants, thrusts, nozzle shapes, combustion chamber shapes, etc.

7 TWO PHASE ROCKET PLUME PREDICTION

7.1 Introduction

Exhaust plume prediction is very important during the development of missile systems that require certain plume characteristics, such as low infrared emissions (for missile detection and recognition) and low radio attenuation (for communication signals and radar cross-section). Although plume measurements are important, they are relatively expensive and a large number of firings are required for a parametric study of design variables. Prediction is also necessary when the plumes of adversary missiles are studied, or when extreme operating conditions are required, such as high humidity or high altitude. Modern flow field prediction is based on computational fluid dynamics (CFD) codes, making use of suitable turbulence models for the mixing of the plume gases. Reaction rate chemistry is used to predict the chemical reactions that may occur in the plume and on mixing with the surrounding air (secondary combustion). Current plume prediction codes do not predict the effect of particles on the plume flow field or predict particle trajectories.

Application codes are used to convert the predicted flow field (velocities, temperatures and chemical constituents) into plume electromagnetic emissions and propagations. Again plume particles are not considered. With improvements in other areas of prediction (such as turbulence modelling and plume chemistry) the inclusion of particles has become more important to the accuracy of plume prediction. Including particles in the prediction may change the predicted plume flow field, but more importantly it allows the trajectories of particles in the plume to be established, which can then be used in the prediction of plume emission and propagation. The specific effects of particles on the plume flow field were discussed in greater detail in section 4.2, together with their role in plume electromagnetic emission and propagation.

There are a number of commercially available CFD codes which can predict non-reacting two phase flows, but only a few of these are capable of being adapted to predict the complex chemical reactions that occur in rocket exhaust plumes. The Plume Science section (DRA, Fort Halstead) has developed two such codes. REP (Rocket Exhaust Plume) is a two dimensional, chemically reacting, single phase, parabolic code, which can handle up to thirty different chemical species and can model sixty different two way reactions using reaction rate chemistry. The code predicts the plume from the nozzle exit plane conditions, which are calculated using one dimensional coding that requires the combustion chamber pressure, nozzle design and propellant composition. A two phase version of REP was developed in the late 1980's (Booth 1989), although it has never been validated with experimental data. The code used an Eulerian approach, where the particle and fluid phases are considered as interpenetrating continua.

To extend plume prediction to three dimensions and improve the modelling of the subsonic regions, the commercially available code PHOENICS was adapted to handle reaction chemistry (PHOENICS - Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series, by CHAM Ltd, Wimbledon). Although the standard PHOENICS coding could predict gas combustion the calculation did not use reaction rate chemistry. The chemical reaction coding developed for the REP code was therefore grafted into PHOENICS. The code has two phase predictive capabilities, but they have not been implemented in rocket exhausts. It is expected that PHOENICS will soon dominate plume prediction because of its three dimensional and sub-sonic capabilities (which allows the prediction of multi-nozzles, scarfed nozzles and adjacent fins), as well as expected future improvements in the code and reduced run times due to increased computing power. REP is still actively used, as it requires less user expertise and takes less time to run (due to the fewer iterations required). During the current research plume particle prediction was based on the PHOENICS coding because of its advanced reaction rate chemistry capabilities and its latent two phase capabilities.

7.2 Two phase flow prediction techniques

7.2.1 Two phase flow variables and processes

The effects of exhaust particles on the plume flow field were discussed previously in section 4.2.1. These phenomena were all related to the ability of each phase to have different values of physical variables. For the prediction of rocket exhaust plumes with a solid second phase the most important of these variables are velocity, temperature (thermal energy), mass and chemical composition. The phases are not independent of each other and are linked by transfer processes, such as drag, heat transfer by radiation or conduction and chemical reaction between the phases. The second phase may melt (or solidify), with associated changes in physical characteristics, and in the liquid phase can have different pressure and turbulence values. Particles may collide with each other or with boundary walls, transferring energy and mass as they do so. They may become miss-shapened during these impacts or become attached to each other (with associated changes in drag etc.).

Gas flow field prediction uses the Navier-Stokes (Euler) equations (see section 7.2.2), which maintain the conservation of mass (continuity equation), momentum and energy. When a second phase is present interactions between phases are allowed for by additional terms in these equations, such as drag in the momentum equation. The particle phase has its own set of conservation equations, with the equivalent transfer terms. The magnitude of these transfers are derived using transfer rate equations, such as the particle drag equation. Turbulence models used in the calculation of the flow field (such as k-w or k-ϵ models) should account for the second phase, as particles have a damping effect on gas turbulence. The reaction rate chemistry used in the gas phase should also be extended to allow for reaction between the two phases, although an extended set of rate coefficients would be required if solid phase reactions occurred.

7.2.2 The standard two phase flow capabilities of PHOENICS - IPSA

There are two methods for including a solid phase in PHOENICS predictions. GENTRA (GENeral TRAcking program) must be purchased as an addition and uses a Lagrangian-Eulerian approach to track separate particles through the flow field (see section 7.2.3). The standard coding includes IPSA (InterPhase Slip Algorithm), which is a Eulerian-Eulerian technique and treats each phase as interpenetrating continua and solves a complete set of flow equations for each phase. Each cell within the flow field is occupied by volume fractions of each phase which can have different values of velocity, temperature (enthalpy), chemical composition, density, particle size and pressure (liquid phases only). The Eulerian equations for the conservation of mass, momentum or energy for each phase have the general form;-

$$\frac{\partial}{\partial t}(\rho_c \phi_c) + \nabla(U_c \rho_c \phi_c) - \nabla(\Gamma \nabla \phi_c) = S_\phi \qquad \text{Eqn 7.1}$$

Where;-

ρ_c is the continuous-phase density.

ϕ_c is the continuous-phase property modelled.

U_c is the continuous-phase velocity.

Γ is an exchange coefficient for ϕ_c.

S_ϕ are the sources and sinks of ϕ_c term.

The source term in each equation allows for the 'appearance' (or disappearance) of mass, momentum or energy from the other phase or from the boundaries, for example thermal energy or mass transferred from the other phase. The magnitude of the source terms are determined by the interphase transport equations (termed 'constitutive relationships'), for example particle drag is calculated from particle size, gas viscosity and density, as well as the relative velocity (the equation used is described in section 7.2.3). Similar relationships are present for the other transport processes and are usually derived experimentally.

The calculation of turbulence is based on the gas phase only, with the turbulent intensity and dissipation determined using only the gas velocity gradients. In reality the introduction of particles into a flow decreases the turbulence intensity. This is partially modelled in IPSA, as the introduction of the second phase decreases the volume fraction of the liquid phase, which reduces its diffusion rate. The second phase cannot directly affect turbulence, so variables such as particle size are not accounted for, although additional source terms can be used to introduce localised turbulence. A full description of IPSA and its operation can be found in CHAM (1993).

7.2.3 Particle tracking coding for PHOENICS - GENTRA

This uses the Lagrangian-Eulerian approach for two phase flow prediction. When calculating the solution of the gas phase flow field it uses Eulerian principles, with a fixed frame of reference. GENTRA then calculates the motion of discrete particles through the flow field using Lagrangian principles (the terms of reference are in respect to the particle). During their journey the particles may transfer mass, momentum or energy to, or from, the gas phase. As the particle enters and leaves each flow field cell its mass, momentum and energy are recorded so that any transfers to the gas phase can be calculated. Once all the particles have been tracked another iteration of the gas phase solution is attempted, using source and sink terms in the gas phase conservation equations to represent transfers from the particles (Eqn 7.1 in section 7.2.2). When the flow field solution has converged again the particles are re-tracked and the process repeated until a stable solution is reached. A schematic of this solution is presented in Figure 7.1 (Moffat 1989).

The particle trajectory is calculated from the particle's momentum equation (neglecting buoyancy) and takes the form;-

$$m_p \frac{dU_p}{dt} = C_D \rho \, (U-U_p) \, |U-U_p| \frac{A_d}{2} + m_p g \qquad \text{Eqn 7.2}$$

Where:-

m_p is the particle mass.

U the gas-velocity (including the turbulent fluctuation if the stochastic model is used).

U_p is the particle velocity.

A_d the particle cross sectional area.

g the gravitational acceleration.

C_D is the particle drag coefficient and is given by;-

$$C_D=\frac{24}{Re}(1+0.15Re^{0.687})+\frac{0.42}{1+4.25*10^4Re^{-1.16}} \qquad \text{Eqn 7.3}$$

Where Re is the Reynolds number and is given by:-

$$Re=\frac{U_p*D*\rho}{\mu} \qquad \text{Eqn 7.4}$$

Where;-

μ is the gas viscosity.

D is the particle diameter.

Particle velocity is determined by integrating equation number 7.2, which gives;-

$$U_p=U_g(U_g-U_{po})\exp[-\frac{\Delta t}{\tau}]-g\tau[1-\exp(-\frac{\Delta t}{\tau})] \qquad \text{Eqn 7.5}$$

Where;-

U_{po} is the initial particle velocity.

τ is the characteristic time and is given by;-

$$\tau=\frac{\rho_p D^2}{18\mu f} \qquad \text{Eqn 7.6}$$

Where;-

ρ_p is the particle density.

f is $C_D Re/24$.

This velocity is then used to calculate the new position of the particle after time Δt using the equation;-

$$X_p = X_{po} + (U_p + U_{po}) \frac{\Delta t}{2} \qquad \text{Eqn 7.7}$$

Where X_p is the new position of the particle and X_{po} the old.

This approach fails if the Δt value is too large compared to the cell size, as the particle would travel too far between trajectory calculations, so some restriction is imposed. The tracking only stops when the particle is removed at a boundary, the particle stagnates, or the number of iterations reaches a preset maximum. Solution of the other transfer equations is similar, again making use of the 'characteristic time' step.

It should be noted that GENTRA does not allow for the effect of particles on gas turbulence, although the effect of the gas phase turbulence on the particle trajectories can be calculated by use of a stochastic turbulence model which randomly adds the turbulence velocity to the gas velocity during calculation of the particle drag. GENTRA is described in more detail in Fueyo (1991).

7.2.4 Selection of suitable two phase coding

Before plume prediction began the capabilities of IPSA and GENTRA were assessed. This basically involved establishing if they were suited to prediction of a rocket plume type flow field, if they produced the required results and if they could operate with the PHOENICS coding developed for plume prediction (ie. with reaction chemistry).

IPSA is designed to predict flows with high particle concentrations, although the lower concentrations typical of an exhaust plume can also be modelled (~0.003% by volume). The particle parameters are set via the boundary conditions and allow particle starting locations to be spread over the nozzle exit plane. The code cannot calculate particle boundary collisions, which may become important if nozzle predictions are to be made and tends to over estimate particle diffusion. Only one particle size can be used in each prediction, which is a major draw back for exhaust plume prediction where particle size varies considerably. The results produced by IPSA provide particle velocity, temperature and chemical composition, but cannot show the spatial variation of particle size in the plume. Because the solution of both phases occurs simultaneously the reaction chemistry coding and IPSA coding must be completely compatible. Single phase plume predictions take many hours to produce a converged solution, so the addition of a second set of variables (such as particle velocities) would extend prediction times and might make convergence difficult to achieve.

GENTRA can only predict flows with low particle concentrations (by volume), but this includes all the exhaust plumes envisaged. The code tracks individual groups of particles through the flow field, so a large number of particle groups must be used to properly model the effect of the particle phase on the flow field. If the effects are to be neglected only sufficient particles to show their dispersion in the plume are required. Additional groups of particles would also be required if a range of particle characteristics were present, such as size, temperature and velocity. The code can calculate particle re-bounds with boundary walls, which is important for nozzle prediction, but not collisions between particles. Particle phase changes can be calculated, although particle break ups and conglomerations cannot. The code also tends to under predict particle diffusion, although stochastic turbulence model can alleviate this. Before the GENTRA code is used a converged gas phase solution can be derived, which will aid the convergence of the two phase solution. The gas phase solution would only need to be recalculated if the interphase transfers were significant, and the process would then have to be repeated until a converged solution was obtained. The GENTRA and reaction chemistry coding would therefore never run simultaneously, which would reduce the chance of code incompatibility.

From the above assessments of the coding GENTRA appears more suitable for use in plume prediction as it can simultaneously handle different particle sizes, predict particle collisions with the nozzle and can track individual particles. The probability of successful convergence with GENTRA is also higher due to its implementation after the convergence of the gas phase solution. Experience with IPSA had shown that the correct setting up of boundary conditions was difficult even with simple flow cases. It was later found that this is a recognised problem with IPSA (Smith 1996) and that significant user expertise is required to ensure correct operation. GENTRA had previously been used in the rocket environment (Moffat 1989), although only inside the combustion chamber and nozzle. This also used a non-reacting gas flow field, but suggests that if compatibility with the reaction chemistry coding can be achieved then prediction inside the motor should be possible. For rocket plume prediction GENTRA offers a solution similar to that produced by IPSA, but also allows multiple particle sizes, boundary collisions and simpler operation.

7.2.5 Methodology for the implementation of GENTRA in PHOENICS

Full implementation of GENTRA into the chemically reacting version of PHOENICS was not anticipated in the timescale of the present research. Instead predictions of the plume were made using chemically reacting version of PHOENICS and separately using the standard PHOENICS coding with the GENTRA particle coding (simplified non reacting plume). The results were then evaluated using the experimental data previously measured. This was carried out in the following manner;-

i) A prediction to simulate the plume from a seeded Heavyweight motor using PHOENICS with reaction chemistry was made to set a 'bench mark' for the simplified two phase predictions. The work was based on these motors as plume particle velocities had been measured and particle collections made (Chapters 5 and 6). The feasibility of combining the chemically reacting plume and GENTRA coding was also assessed.

ii) A simplified plume was predicted (ie. no chemistry or heat transfer) based on the nozzle velocities from (i) and particles were then tracked through this plume using GENTRA.

iii) The results from (i) and (ii) were then evaluated by comparing them with experimental results. Trends in particle behaviour were also noted upon.

iv) Recommendations were made for future work.

The plumes produced by the Heavyweight motors with different levels of particle seeding were found to be nearly identical when predicted using the chemically reacting version of PHOENICS. This was due to the low levels of added particles and their inert nature. The results for the 2% seeded motor are presented here (Figures 7.3 and 7.4) and were predicted using version 3.0.2 of the plume prediction software, which is based on PHOENICS version 1.6. The nozzle exit plane conditions, used as the starting point for the plume prediction, were derived using in-house codes that modelled the combustion of the propellant and its flow through the nozzle. The air surrounding the plume was static and standard sea level atmospheric conditions were used. The predictive domain was axi-symmetric with a 1m radius and a length of 5m, with a grid density of 30 cells radially and 90 longitudinally.

Attempts were made to implement the GENTRA coding into the reacting plume prediction, but incompatibility of the two sets of coding prevented its use. These incompatibilities were identified by the code originator Dr A.G.Smith (S+C Thermofluids), although the time and effort needed to implement the required changes in the coding was considerable and could not be completed in the timescale of the current research. It was therefore deemed most appropriate to proceed using GENTRA (Version 2.1) operating in a simplified plume predicted using the standard PHOENICS (Version 2.1).

The flow field used for the simplified plume was axi-symmetric with a radius of 0.8m and a length of 3m. All boundaries were set to sea level atmospheric conditions (air standard dynamic values), with a 2324m/s axial velocity over the 15.625mm radius of the nozzle exit plane and 10m/s over the remainder of the boundary. There were 20 cells radially and 50 longitudinally, with a higher grid density towards the nozzle and the centre line. A k-ϵ turbulence model was used to predict the mixing of the plume with the entrained air. Several predictions were performed with minor variations in the starting conditions to ensure reproducibility and robustness. Once the flow field solution was established GENTRA was then used to predict the particle trajectories. Gravitational and buoyancy forces were neglected due to the high particle velocities. The initial conditions for each particle were set (position, velocity, diameter and density) and the boundaries through which particles could leave the domain defined. Various running parameters were also needed to ensure suitable time steps were used and to limit output resolution. Because relatively few particles were added to the flow they had no effect on the flow field (ie. on subsequent predictions of the gas velocity they were seen not to change), so only one GENTRA run was required for each prediction. Predictions were made using the particle starting positions and velocities stated below for particles diameters of 0.5μm (smaller sizes made no difference to the computation), 4.0μm and 20μm, with a particle density of 6000Kg/m^3 (these values are typical of the zirconia collected from inside the plume in Chapter 5). The initial particle conditions were as follows;-

i) Particles on the centre line of the nozzle's exit plane with axial velocities of 1000m/s, 1500m/s, 2000m/s and 2500m/s (to show the effect of particle initial axial velocity on their subsequent velocity in the plume).

ii) Particles positioned at the edge and middle of the nozzle's exit plane with velocities of 1000m/s, 1500m/s, 2000m/s and 2500m/s (to show the effect of particle initial axial velocity on their radial movement in the plume).

iii) Four particles spread evenly across the nozzle exit plane with axial velocities of 2000m/s (to show the particle distribution in the plume).

iv) Repeat of (iii), but with additional initial particle radial velocities (to show the effect of initial particle radial velocity on the particle distribution in the plume).

v) Repeat of (iii), but with the stochastic turbulence model active (to show the effect of gas turbulence on the particle distribution in the plume).

vi) Repeat of (iv), but with the stochastic turbulence model active (to show the combined effect of initial particle radial velocity and gas turbulence).

7.3 Evaluation of predictions with experimental results

7.3.1 Assessment of the gas phase predictions

The accuracy of the predicted gas phase velocities were assessed before the particle phase was considered. In Smith (1989) a parametric study was performed to determine the ability of PHOENICS to predict exhaust plumes and comparisons were made with experimental results (these were non reacting flows). It was found that PHOENICS over predicted the mixing rate of the plume after the initial shock (ie. it under predicted the plume's core length) and smeared out any subsequent shocks that may have occurred. This rapid mixing was thought to be partly attributable to the inadequacy of the turbulence model (k-ϵ) and numerical diffusion. The reaction chemistry version of PHOENICS developed for plume prediction was based upon this work so also under predicts the core length of the plume and predicts less shock structure, although this is not quantitatively known as there is a lack of comparable experimental data in reacting plumes (one of the reasons for this present work). Research has recently been carried out to incorporate higher order numerical schemes (Rawley 1996) and more appropriate two equation turbulence models (Kingston 1996), but these are not implemented in the present plume coding.

The particle trajectory predictions were carried out in a simplified (non reacting) plume predicted using the standard PHOENICS coding and this flow field varied in a number of ways from that predicted using the reaction coding. The centre line axial gas velocities in both predictions (Figure 7.2) had a common initial value at the nozzle (2324m/s), the reacting plume's velocity then slightly rose compared to the non-reacting one. At 10cm from the nozzle the non reacting plume's velocity began to fall, while the reacting plume's velocity remained high until 20cm. The simplified plume's axial velocities also reduced more rapidly away from the plume's centre (Figures 7.3 and 7.5) and was approximately 50% smaller than the chemically reacting plume. The radial velocities (Figures 7.4, 7.6 and 7.7) were both of a similar form, with positive radial velocity throughout the plume and small regions of high positive radial velocity

($\sim$75m/s) near to the edge of the nozzle. These regions extended downstream either side of the centre line and were almost mirrored by regions of negative radial velocity in the surrounding air.

When comparing the predicted results with plume measurements it should be noted that the plume predicted using the reaction coding was smaller than that observed experimentally and, as stated before, the simplified plume prediction used for particle trajectory calculation was even smaller (Figure 7.2). However, the initial velocities were similar in the two predictions, so although particles will not be subject to the velocities for the same periods of time, they will experience the same magnitudes. Therefore initial particle accelerations will be similar, but the final velocities reached may differ (the difference being dependent on how much the particles have been accelerated before the gas velocities begin to differ). The particle dispersion through the plume will also follow similar trends, but an exact comparison between prediction and experimental data will not be possible because of the differences in the flow field.

7.3.2 Evaluation using particle velocity data

Measurements of particle velocity were made along the centre lines of zirconia seeded Heavyweight motors (see section 6.5). Some measurements were only partially successful, although results were obtained between 1cm and 60cm downstream from the nozzle (Figure 6.37). There was some variation between measurements ($\sim$10%) and there was also a time dependency during each measurement ($\sim$10%). The latter may be the cause of variations in the measured velocity profiles (shock structure may also be influential). The particle velocity profiles measured during firings A8 to A11 (section 6.5) were used during evaluation of the predictions. During the initial velocity profile measurement in firing A11 (Figure 6.36) a particle velocity of 2150m/s was recorded at 1cm from the nozzle, increasing to 2450m/s at 15cm downstream and then slowly rising to 2500m/s over the remaining length of measured plume (up to 36cm from the nozzle). The second measurement during firing A11 and the measurements during firings A8 to A10 showed a lower velocity of approximately 2300m/s between

12 to 60cm from the nozzle, although there were some higher velocities measured for short periods. This was thought to be due to the temporal variation in particle velocities in the plume (illustrated by the variation in measured velocity when the measurement position was stationary). The increase in particle velocity in the region 1cm to 15cm from the nozzle was due to drag forces caused by higher gas velocities (see section 7.2). In the remainder of the measured plume (15cm-60cm) the difference between particle and gas velocities was only marginal, causing negligible particle acceleration.

The highest centre line gas velocity predicted using the reaction chemistry coding (Figure 7.2) was 5cm from the nozzle (2380m/s) and the velocity remained above 2300m/s until 20cm downstream, where it began to fall more rapidly. The predicted gas velocities were therefore higher than the measured particle velocity between 1cm to 10cm from the nozzle (where the particles were accelerating) and then of similar magnitude further downstream until 20cm from the nozzle, where the predicted gas velocity fell quickly, while the particle velocity remained high. The difference in the velocities between 1 and 10cm was due to the velocity lag of the measured particles, which decreased due to the drag forces. In the region 20 to 60 cm from the nozzle the measured particle velocity remained higher than the predicted gas velocity due to the particle's momentum and the higher than predicted gas velocities in the real plume (as mentioned in section 7.3.1). The gas velocities in the simplified plume prediction (used for the particle tracking) dropped even sooner than the reacting plume prediction and should be noted when comparing with measurements.

The calculation of particle velocities relies upon their initial velocities set at the nozzle exit plane. As these were not known a parametric study of initial particle velocity was performed (as stated in section 7.2.5(i)) to assess their effect on particle trajectories in the simplified plume (Figures 7.9 to 7.11). Initial particle velocities ranging up to the gas velocity were used in the predictions (1000m/s, 1500m/s 2000m/s and 2500m/s) to establish the one which simulated the measured results (Figures 6.37 and 7.12). The 0.5μm particles responded very quickly to the gas velocity (the initial velocity being almost immaterial) and did not exhibit the gradual rise in velocity that was measured.

The velocities of the 4.0μm particles were more dependent on their initial velocity. The 4.0μm particles launched at 2500m/s only significantly decelerated once there was a large drop in gas velocity. The particles launched at 2000m/s were initially accelerated by the higher gas velocity, the rate decreasing as they approached the gas velocity. Those launched at 1000m/s and 1500m/s exhibited similar trajectories, but with increased initial acceleration. The 20μm particles were highly dependent on their initial velocities, with only gradual changes due to the drag forces. The velocity of the 20μm particles with an initial velocity of 2500m/s only changed significantly when there was a large fall in gas velocity and even then maintained a much high velocity than the gas. The other 20μm particles launched at lower initial velocities were slightly accelerated by the higher gas velocities, but never approached the gas velocity and again maintained higher velocities after the gas had decelerated.

Although 0.5μm, 4.0μm and 20μm diameter particles were used in the predictions, only the 4.0μm particles should be evaluated using the measured velocities, as in section 5.5.2(v) it was shown that the average cross-sectional area for zirconia particles in the plume was between 4.15μm and 4.57μm (this size being the one that scattered most laser light and therefore the size that dominated the anemometer measurement). The 4.0μm particles launched at 2500m/s did not exhibit the gradual acceleration exhibited in the measurements, while those launched significantly below the gas velocity (1500m/s) accelerate at a rate much higher than that measured (Figure 7.12). Intermediate initial particle velocities were also tried, but were found not to improve the velocity profile. For the predicted particles trajectories to exhibit the same velocity profile as the measurements an initial particle velocity of 2000m/s was used, although the particle velocities decreased earlier due to the shorter length of the predicted plume.

7.3.3 Evaluation using particle collection data

During the particle collection measurements (section 5.5.3) the following trends in particle distribution across the plume were identified;-

- Most of the particles were in a central core region with a surrounding region of much lower particle concentration (eg. Figure 5.16).
- Particles collected away from the central region of the plume tended to be larger (eg. Figure 5.50).
- Particles of all sizes were collected in the outer region (eg. Figure 5.51).
- There may be some localised regions of higher particle concentration (eg. Figure 5.17).

Because the initial particle velocities were not known at the nozzle exit plane (although particle velocity was estimated in section 7.3.2 to be 2000m/s) predictions were made to determine their influence on the particle trajectories (as stated in section 7.5.2(ii)). Particle diameters of 4.0μm and 20μm were used together with initial velocities of 1000m/s, 1500m/s 2000m/s and 2500m/s, and these were initiated at the edge of the nozzle (to show the furthest extent of the plume) and at the middle of the exit plane radius (to represent particles typical of the majority of the plume).

The trajectories of the 0.5μm diameter particles were almost independent of their initial velocity (Figure 7.13). For both launch positions the initial velocity of the 4.0μm particles made a negligible variation in the radial distance travelled over the predicted domain (Figure 7.14). The 4.0μm particle launched at 1000m/s at the edge position had the greatest movement and travelled 6% further radially than the other particles launched at the higher velocities, otherwise all trajectories were very similar. The 20μm particles launched between 1500m/s and 2500m/s again showed negligible variation in radial movement (Figure 7.15), although particles launched at both positions at 1000m/s travelled 15% further radially than the other particles launched at higher velocities. The increase in radial spreading with lower initial axial velocities was due to the increased time these particles were exposed to the radial gas velocities. It was concluded that if the initial axial particle velocities are 1500m/s or greater they will have relatively little effect on particle distributions in the plume (although their residence times in the plume will alter). It was also noted that the smaller particles travelled further radially than the larger ones, due to the higher ratio of particle drag to particle inertia.

An initial-particle velocity of 2000m/s produced results comparable with the velocity measurement data (section 7.3.1), so this velocity was used in the prediction of the trajectories of particles evenly distributed across the nozzle's exit plane (as stated in section 7.2.5(iii), see Figures 7.16 to 7.18). Again particles with diameters of 0.5μm, 4.0μm and 20μm were used to simulate the zirconia seeding. The results showed that for all the particle sizes the ones launched near to the edge of the nozzle moved furthest radially during their passage through the plume, which was due to the increased radial velocities away from the centre line (Figure 7.7). All the particle sizes followed fairly smooth trajectories and the 0.5μm particles travelled the furthest radially (0.037m, 2m axially), as they acquired greater radial velocity from the plume gases. The 4.0μm particles travelled radially to 0.033m and the 20μm ones to 0.023m. All the particle sizes showed relatively little radial movement compared to their axial movement, which corresponds to the central core region of particles seen experimentally. Experimentally there were also particles collected outside this region and an increase in larger particles towards the edge of the plume, both of which were not predicted. A possible explanation for this could be that the particles leaving the nozzle may have an initial radial velocity gained during their passage through the nozzle or whilst inside the combustion chamber and this was therefore investigated.

As experimental values for the particle velocities at the nozzle exit plane were not known the radial velocity component was calculated using the assumption that the velocity had caused the particle to move radially inside the nozzle to its position at the exit plane, ie. the radial component was equal to the tangent of the angle of the particle's trajectory from the nozzle's throat to its exit plane, multiplied by the axial velocity component (Figure 7.19). On average this under estimates the radial velocity and would not allow for particles that gained radial velocity in the combustion chamber, which may also cause them to collide with the nozzle wall. The previous predictions were repeated with the additional of initial particle radial velocities (as stated in section 7.2.5(iv), see Figures 7.20 to 7.22). The 0.5μm particles moved further radially on leaving the nozzle than in the previous case, but soon became dominated by the gas velocity and reverted to trajectories similar to those exhibited without the addition of initial radial velocity, resulting in only a slight increase in the radial movement over the 2m considered (8% more, 0.04m total radial movement). The 4.0μm particles maintained their radial velocity for longer and therefore moved further radially. Their overall radial movement was 65% greater (0.055m total radial movement) than without initial radial velocity and this was restricted by the outer particles reaching the edge of the expanding plume (where the gas radial velocity becomes negative), which caused a region of higher local particle concentration. The velocities of the 20μm particles were even less affected by the plume gases, resulting in an increase in radial spread of 770% (0.2m total radial movement). Again the particles that reached the edge of the expanding plume were decelerated, causing a local concentration of particles (although in a different position to the 4.0μm case).

The addition of radial velocities to the initial particle conditions caused the particles to travel further radially and this process was influenced by particle size. This caused a bias towards larger particles away from the plume's centre line and a local regions of higher particle concentration due to the particles reaching the edge of the expanding plume. However, experimentally particles of 0.5μm and 4.0μm sizes were collected further away from the plume axis than predicted (even allowing for the larger size of the real plume). It was noted in section 7.2.4 that GENTRA tends to under estimate particle diffusion and it could not handle particle collisions. GENTRA does, however, have an option that adds the effect of gas turbulence on the particle trajectories. By using the stochastic turbulence model a component of the turbulence velocity is randomly used in the particle drag calculations. This was used to predict the paths of particles of each size spread across the nozzle exit plane with axial velocities of 2000m/s (as stated in section 7.5.2(v), see Figures 7.23 to 7.25). It should be noted that if the predictions were rerun the paths would change due to the random element, but if enough predictions were performed then the average of the paths would approximate to the prediction without the turbulence model.

The effect of turbulence was most significant on the 0.5μm sized particles, which exhibited large changes in both radial and axial velocities in regions were plume was mixing with the surrounding air (this is reflected by increased kinetic energy, see Figure 7.8). Particles launched near to the edge of the nozzle encountered the increased turbulence first, so tended to be dispersed more. The particle trajectories were very random and some particles passed through the centre line. The particles travelled up to 0.275m radially, 640% further than predicted without turbulence. The 4.0μm particles had smoother trajectories, but still had substantial variations in radial velocities and a radial movement of 0.273m, 725% further than before. The 20μm particles were less affected by the turbulence, resulting in much smoother trajectories and a radial movement of 0.083m, 260% further than previously predicted. The inclusion of turbulence effects in the modelling therefore provides a mechanism for the plume particles to spread over a much wider area.

A further set of predictions were made combining initial particle radial velocity and the stochastic turbulence model (as stated in section 7.2.5(vi), see Figures 7.26 to 7.28). The radial extent of all particle sizes at 2m downstream was predicted to be 0.3m, showing that the effect of the initial radial velocity on the larger particles was balanced by the effect of the gas turbulence on the smaller ones. It should be noted that if different initial velocities and turbulent intensities were used or the operation of the stochastic turbulence model altered, then this balance might not occur.

During this study GENTRA predicted a plume with a central core of high particle concentration with a bias towards larger particles at its centre. If initial particle radial velocities were added then the larger particles travelled further radially, some reaching far outside the central core. Regions of higher particle concentration were also formed. By using the stochastic turbulence model the effect of gas turbulence were added to the particles trajectories, which caused some of the smaller particles to travel much further radially. By including the effects of initial radial particle velocity and gas turbulence, a much larger region of lower particle concentration (of all sizes) was predicted that surrounded the previously predicted central core of high particle concentration.

The main limitation on these predictions was the lack of nozzle exit plane particle velocities and particle concentrations, although the effect of varying particle velocity was examined (initial turbulence intensity is also important, particularly if the stochastic model is used). In reality particles may be concentrated towards the centre of the nozzle, due to the rapid expansion through the nozzle, with only the smallest particles present at the edge of the nozzle. Therefore, although it was shown that the 20μm particle with initial radial velocity travelled further radially than the smaller sizes, in reality the larger particles may not gain any significant radial velocity during their path through the nozzle for this to occur. However, before the particles reach the nozzle they may have acquired significant velocities inside the combustion chamber which may effect their flow through the nozzle and plume.

7.4 Conclusions and recommendations from the predictive work

7.4.1 Conclusions on the comparison of predictions and measurements

The magnitudes of the predicted gas velocities in the chemically reacting plume were similar to the particle velocities measured on the plume centre line, although the axial extent of the higher velocities was smaller. The velocities in the non reacting prediction of the plume decayed more rapidly, although their initial magnitudes were similar to the reacting plume's. The predicted forces accelerating the particles (caused by the higher gas velocity) therefore decayed prematurely, resulting in lower predicted particle velocities than those measured. GENTRA was used to predict particle trajectories in the simplified plume and showed that particles with diameters of 4.0μm (the size which scattered most laser light during the velocity measurements, determined from the particle collection data) had a similar velocity profile to the anemometer measurements, although the initial particle velocity at the nozzle exit plane had to be established by a parametric study.

The various predictions made with particles distributed across the nozzle exit plane produced a plume with a central core region of high particle concentration and a surrounding region of lower concentration, both of which were observed experimentally. The radial movement of particles was dependent on their size and their initial radial velocity (the latter only when larger than 0.5μm), which resulted in localised concentrations of some sizes. Initial particle conditions are required for accurate prediction of particle trajectories in the plume and could be obtained by measurement at the nozzle exit plane or by predicting the flow inside the combustion chamber and through the nozzle. PHOENICS has been used to perform single phase non reacting predictions of the flow inside a rocket motor by Ludwig (1988) and chemically reacting flows through nozzles by Rawley (1995).

7.4.2 Conclusions on flow phenomena

Particles exit the rocket motor's nozzle with velocities lower than the gas, the exact amount depending on particle's history inside the motor and nozzle. They are then accelerated by the faster gas until either the drag forces become insignificant (the particle and gas velocities being similar), or the gas velocity drops below that of the particle (due to mixing with the surrounding air). Particle acceleration rate is very dependent on the particles size, shape and density (ie. particle drag to inertia ratio). As particles pass through the plume they are also accelerated by radial gas velocities, causing them to travel radially. This effect is greater with smaller particles (ie. higher ratio of drag to inertia), while the larger particles' trajectories are dependent on their initial velocities, which causes the larger particles to move out further radially than the smaller ones. Regions of higher particle concentration may also form where particles of different size congregate due to velocity gradients in the plume. In this way most of the particles inhabit a fairly small central region of the plume ($\sim$a few nozzle radii wide), with only the larger particles appearing further away from the centre line. However, there is also a random element to the particle trajectories, caused by their history before reaching the nozzle exit plane and the effect of gas turbulence and particle collisions in the plume. This results in lower concentrations of particles of all sizes over a large area surrounding the central plume region of high particle concentration.

The trajectories of particles through the plume are dependent on; the gas velocities in the plume, the initial particle concentrations and the initial particle velocities at the nozzle exit plane. The magnitude of these effects are determined by the particles ratio of drag and inertia. The smaller particles ($\sim 0.5\mu m$) are highly influenced by the plume velocities and the effect of turbulence. With larger particle, where their inertia is significant compared to their drag, conditions at the exit plane become more important, as their initial velocity may decide their path through the plume. Although larger particles are less affected by gas velocities in the nozzle, there are other phenomena which may impart velocity to them, such as the flow inside the combustion chamber and collision with the chamber or nozzle walls.

The effects of particles on the plume flow field were discussed in greater detail in Chapter 4. Because of the low particle concentrations considered during these predictions such effects were not observed. In order to simulate higher particle concentrations a greater number of initial particle locations would be required, each representing a group of particles of a certain size and density. There were a number of particle phenomena that were not measured or predicted, such as increased drag due to non-spherical particles, changes in particle shape, particle break ups or agglomerations, combustion of the particle and heat exchange ($\sim$particle temperature). Some of these affect the particle sizes present in different regions of the plume, for example particle agglomeration may result in larger particles. Particle temperature may influence the plume flow field, but it is also very important for the prediction of plume electromagnetic signature and must therefore be considered in it own right.

7.4.3 Recommendations for future plume predictions

The following recommendations are suggested to improve the prediction of plumes containing particles;-

i) Implement GENTRA in the chemically reacting version of PHOENICS currently used to predict exhaust plumes.

ii) Predict particle trajectories inside the nozzle and combustion chamber to provide exit plane conditions for plume prediction.

iii) Increase the particle variables and processes that can be modelled, such as particle temperature, particle shape, particle combustion and particle conglomeration or breakup.

iv) Include the effects of the particle phase on the gas flow field by the addition of multiple particles of representative size and mass.

The following complimentary research is also suggested;-

i) Plume particle collections be made with greater spatial resolution.

ii) Plume particle velocity measurements be made in other areas of the plume, including at the exit plane.

iii) Investigate the final use of particle trajectory data, for example its inclusion in plume infrared signature prediction.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The planning and management of the research programme was analyzed to establish which managerial techniques were most appropriate to the research environment. Although the conclusions were fairly general in nature they were found to be important during the current research programme. One of the main problems encountered was the communication of the project plan to the supervising panel. Management software was used to produce planning charts that illustrated the proposed research and recorded progress. It was found that care had to be taken to avoid the charts becoming over large or too confusing. The software identified the critical paths of the activities, periods of work overload and potential over runs of the work programme. These could then be allowed for in the planning of the research. The benefits of this would have been maximised if the software had been used from the start of the project, but most of the planning had already been performed before the software was implemented. The size of the present research was large enough to justified the use of the software, although its late implementation and the author's inexperience in its use off-set any real benefits.

Communication was also found to the main theme of good management of experimental trials. A mixture of written and oral communication was required to effectively convey information to those involved in the firing and measurement of rocket motors. The communication of information from the experimenters back to the trials organiser was also important. Various stages were identified in the planning and management of trials, such as writing trials specifications, and ways in which they have been addressed were examined. During planning of the trial, tasks must be allocated to individuals so that they take responsibility for them. The importance of each measurement (to the trials sponsor) must be established so that correct decisions can be made should there be clashes in the operating requirements of different pieces of measurement equipment. The running of a trial depends on the people involved, so it is therefore important that they are properly informed and feel part of a team. They will then start to become pro-active to the problems that might occur and take an active involvement in making sure the trial is successful, rather than just the success of their own measurement. After each trial it is important to obtain feedback from those participating, the sponsor and the end users of the data, so that deficiencies can be addressed in order to enhance future trials.

The cost and benefits of the research were examined. The cost of the research was calculated, but the contribution towards the ultimate benefit of improved missile systems could not be quantified due to the long term nature of the research. However, by using the information generated by the research as a measure of its success, it appeared that it compared well with other research programmes in the ratio of information gained to cost incurred. As well as particle data there were other benefits, such as developed techniques for particle velocity measurement and particle collection, although they all require marketing to ensure they are exploited in the future. As mentioned the cost of the research was quantified, and it became apparent that by far the largest expenditure was on manpower. It is therefore here where the greatest savings could be made, especially by the proper implementation of management techniques stated previously.

During the review of literature on rocket plumes it was established that there is considerable interest in plume particles, although previous research had been limited. Other researchers interested in plume technology were identified, although their involvement in plume particles research varied. The technical reasons why the research is important were discussed and the contribution of plume particles to the electromagnetic signature of the plume illustrated by use of experimental results in the ultra violet, visible and infrared wavebands. The constituents of rocket propellants that may form plume particles were identified and the processes involved examined. Previous research on the measurement of plume particles was reviewed, such as the collection of alumina particles from the Space Shuttles exhaust cloud and the measurement of particle optical properties.

The Centrisep proved to be the best technique for particle collection in the exhaust plume, collecting undamaged particles in sufficient quantities for full analysis ($\sim$0.5 grams), although they were unable to operate in the hottest regions of the plume (above 1500^{o}C) and at supersonic velocities. Particles collected from the plumes of a number of different rocket motors were analyzed to provide data on particle chemical composition, shape and size. The particles were found to be dependent on the propellant composition, for example aluminium in the propellant produced aluminium oxide spheres in the exhaust, while refractive material (ie. zirconia and silicon carbide) became semi-molten in the plume and formed into clusters. The particle sizes varied between motors, with some correlation with the design of the motor, particularly the case construction. The majority of particles in the plume were found in the central region, although there was a much larger region of lower particle concentration surrounding it. The particles collected further away from the centre of the plume tended to be larger. Additional collections may be required in the future to conclusively establish this and may also reveal localised particle variations.

The measurement of particle velocity in the plume proved to be more convoluted than envisaged due to the peculiarities of the anemometer. The initial trial proved that the anemometer (Michelson interferometer) could operate in the exhaust plume environment, but also showed that it can give incorrect particle velocities (~300m/s) due to the saturation of the photo multiplier tubes by wide band background radiation emitted by the plume. This was only discovered in the second plume measurement trial, but was consequently remedied by the use of a narrow band filter in the detection optics, resulting in the successful measurement of particle velocity profiles along the centre line of the Heavyweight motors' plume. In support of the rocket plume measurements a controllable high speed flow was measured to establish the accuracy and reliability of the anemometer. Miniature rocket motors were also measured to experimentally demonstrate the 'roll over' of the system's output voltage when its dynamic range was exceeded. By the end of the research the anemometer system had been developed to a level where accurate measurements of future rocket plume could be confidently made.

Progress was made towards the prediction of a two phase chemically reacting plume by using the GENTRA coding to track particles in a non reacting exhaust plume predicted using the PHOENICS CFD code (ie. in a simplified plume). PHOENICS was used because it has been developed to predict chemically reacting single phase plumes, while also having inherent two phase coding, although both capabilities had not been used together. The Heavyweight motor's plume predicted using the chemically reacting version of PHOENICS was smaller than that measured experimentally by the anemometer. The non reacting coding predicted an even more undersized plume, but contained velocities of similar magnitude to the reacting plume. Particles in the non reacting plume would therefore experience similar accelerations to those in the reacting plume (and the real plume), but the duration of the acceleration would be less, resulting in lower particle velocities and reduced radial motion. Using the GENTRA coding particles of 0.5μm, 4.0μm and 20μm diameter with axial velocities of between 1000m/s and 2500m/s were launched along the centre line of the non reacting plume. The anemometer measured the velocity of the particle size that scattered most laser light and this corresponded to the particle diameter of average cross-sectional area collected from the zirconia seeded Heavyweight motor's plume, which was between 4.15 and 4.57μm according to collection position. By comparing the predicted velocity profiles with those measured by the anemometer it was shown that particles with a 4.0μm diameter and an initial velocity of 2000m/s produced a particle velocity profile comparable with experimental data, although the predicted particles decelerated much sooner due the smaller size of the predicted plume.

Particles were launched at various positions across the nozzle exit plane in order to compare the particle predictions with particle collections. It was predicted that if the particle's axial velocity at launch was greater than 1500 m/s it had negligible effect on the particle's radial movement during its trajectory through the plume and therefore a common axial velocity of 2000m/s was used for all subsequent predictions. The radial spreading of all the particle sizes during their passage through the plume was small, analogous to the central region of high particle concentration measured experimentally. By adding initial radial velocity to the particles the radial movement of the larger particles increased, resulting in larger particles being able to leave the central region and the formation of localised particle concentrations. The stochastic turbulence model available within GENTRA was used in the predictions to provide a process were by the smaller particles could also reach this outer region.

The predictions showed that the predicted plume had a central region of high particle concentration, with a bias towards larger particles away from the centre of the plume caused by initial particles radial velocities and this also allowed larger particles to populate an outer region of lower particle concentration. Smaller particles were also present in this outer region due to the random effects of gas turbulence on their trajectories. The predictions therefore showed similar trends to the experimental measurements, although in the future prediction could be improved by use of reaction chemistry, the incorporation of other particle phenomena (eg temperature, and collisions) and by establishing the particle boundary conditions at the nozzle exit plane (as defined in the recommendations).

The ultimate aims of 'plume science' are to be able to control and predict rocket plume characteristics (ie. the plume's electromagnetic signature and its propagation of electromagnetic signals, see section 1.2). By meeting the objectives set in section 1.2 the present research has contributed towards these aims by increasing the information known about the size, chemistry and distribution of particles in the plume (which can be used in the prediction of plume flow fields and their electromagnetic emissions and propagation), by measuring particle velocities (which can be used in the validation of plume predictions) and by initiating the development of coding for the prediction of two phase chemically reacting plumes. Because of the enormity of the subject there is still considerable work to be performed before plume particles are properly understood and definitive predictive capabilities are developed. It is hoped that the recommendations made will successfully guide future plume particle research towards the achievement of these aims.

8.2 Recommendations

In each chapter of the thesis relevant recommendations were made. The aim here is to suggest a coherent programme of future research, whereby the experimental work can properly support the development of the computational prediction of two phase plumes. The management techniques previously mentioned should be implemented during the course of future research, such as the use of managerial software for the planning of the project, the analysis of costs and benefits, and the adoption of the suggested methodology for the management of experimental trials. The predictive elements that were identified for development are;-

i) The implementation of the GENTRA coding in the reaction chemistry version of PHOENICS that is presently used for plume prediction.
ii) The calculation of particle velocities and concentrations at the nozzle exit plane by prediction of their trajectories through the nozzle and inside the combustion chamber,

again using a reaction chemistry version of PHOENICS with GENTRA.

iii) The inclusion of particle temperature in such predictions, as it is required in the calculation of plume electromagnetic signatures.

iv) The possibility of enhancing the code by adding secondary particle phenomena should be considered, such as particle combustion, phase change, break up, conglomeration and the effects of the particles on the gas flow field (principally their effect on gas turbulence).

Further experimental measurements are required to properly validate the predictive work, to aid in its development and to properly understand plume particle phenomena. The following are suggested;-

i) Further measurements in the Heavyweight motor's plume to produce accurate contours of particle velocities, concentrations and sizes for use as a test case in code development.

ii) Measurements in the plumes of rocket motors with parametric changes in propellant and motor design to establish the dependency of particle characteristics.

iii) Measurements of the particle velocities, concentrations and sizes at the nozzle exit plane for use as input values for plume prediction and to aid in the development of nozzle coding. A non-intrusive size measurement technique would need to be developed for this.

iv) Active participation in the development of measurement techniques that may prove suitable for operation in the hostile environment of the exhaust plume, such as Doppler Global Anemometry and in-situ laser diffraction particle sizing.

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APPENDIX A

Rocket motor propellant compositions and thrust curves

Propellant composition of Experimental Aluminised Composite motor

Ammonium Perchlorate	60%
Ammonium Picrate	17%
Aluminium	12%

The remaining 11% is made up from;-

Polymer	80%
Plasticiser	15%
Minor ingredients	5%

Propellant composition of Cast Double Base (CDB) motor

Nitro cellulose	56.0%
Nitro glycerine	32.25%
Inert plasticiser	6.9%
Lead salts	3.5%
Stabilizers	1.35%

Propellant composition of Heavyweight motors

	No seeding	**1% seeding**	**2% seeding**
Nitro cellulose	41.7%	41.7%	41.6%
Nitro glycerine	45.9%	45.3%	45.0%
Inert plasticiser	6.9%	6.9%	6.9%
Stabilizers	1.0%	1.0%	1.0%
Salts of potassium or lead	4.7%	4.7%	4.7%
Zirconia or Silicon carbide	0.0%	1.0%	1.0%

Propellant composition of CRV7s

	C14	**C15**
Ammonium perchlorate	69.4%	87.45%
Aluminium	18.0%	-
Ferric oxide	0.6%	0.55%
Binders	12.0%	12.0%

The above are percentages of the main constituents. Minor amounts of other compounds are present, including;-

	C14	**C15**
Calcium salt	yes	yes
Zirconium silicate	no	yes

Other sources of plume material in the CRV7s

i) There is an aluminium foil barrier between the propellant and the case insulation material. Approximately 12g of the foil is burnt in the last 25% of the motor firing.

ii) An 'aft restricter' is positioned at the end of the propellant charge. This consists of 55% alumina hydrate and 45% organic binder. It weighs 10g and approximately 70% is eroded during a firing.

APPENDIX A continued;-

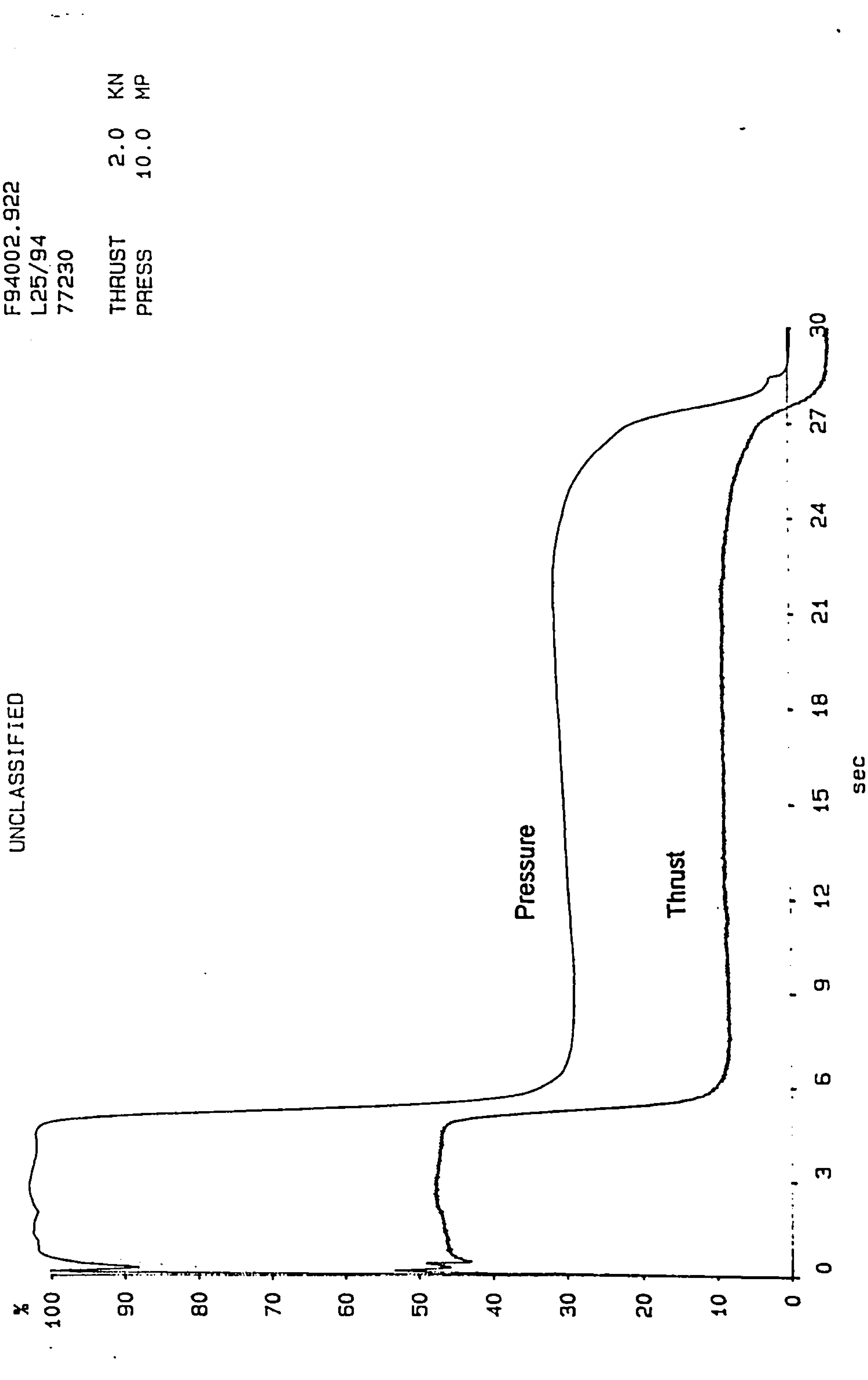


Figure A1 CDB motor thrust and chamber pressure curves

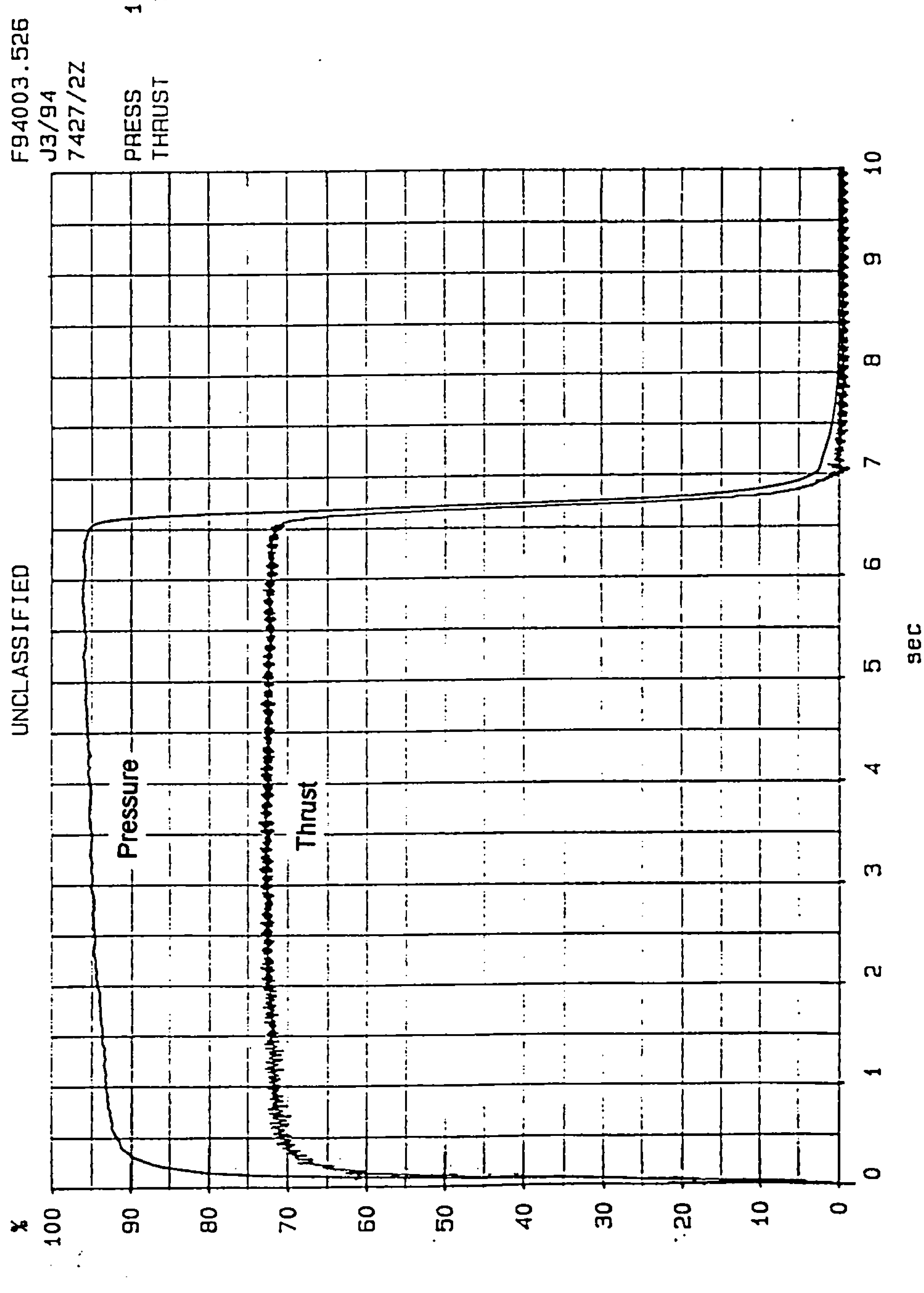


Figure A2 Heavyweight motor thrust and chamber pressure curves

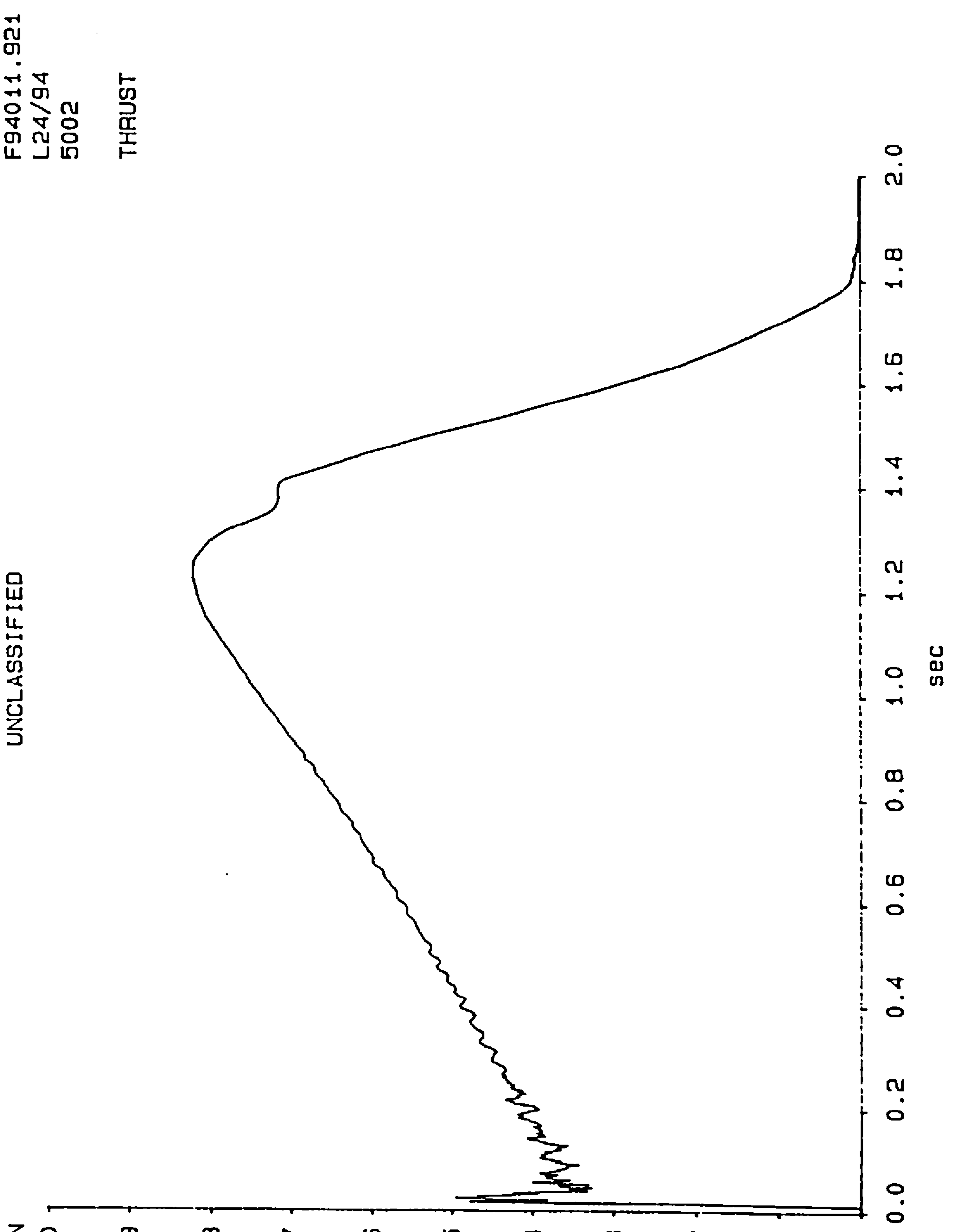


Figure A3 CRV7 C14 motor thrust and chamber pressure curves

APPENDIX A continued;-

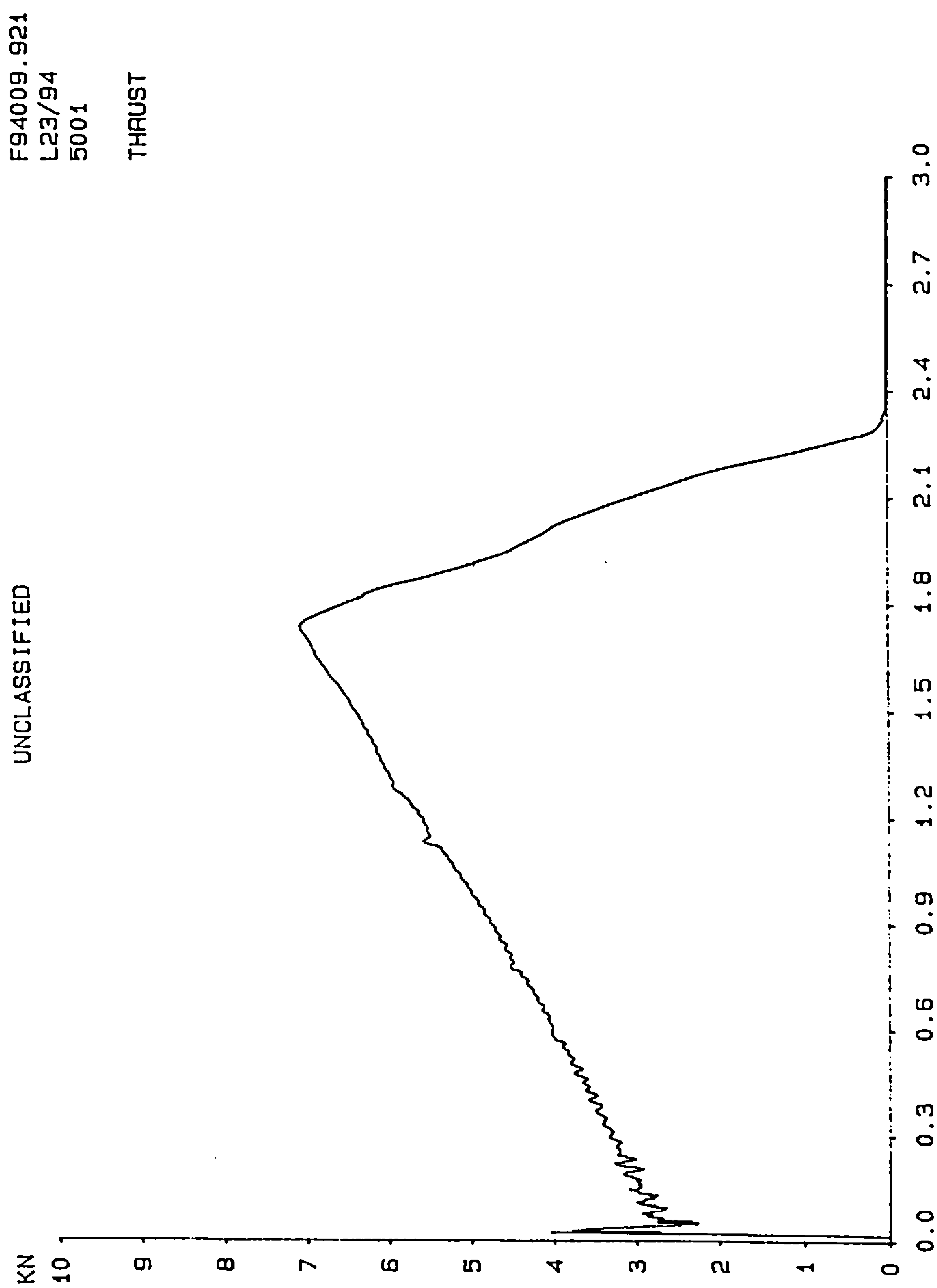


Figure A4 CRV7 C15 motor thrust and chamber pressure curves

Engine Type	Total Impulse		Average Thrust		Propellant Weight Grams	Thrust Curve Number
	Pound-seconds	Newton-seconds	Pounds	Newtons		
1/2A6-	0.28	1.25	1.30	5.80	1.56	1
A8-	0.56	2.50	1.73	7.70	3.12	2
B4-	1.12	5.00	0.93	4.15	6.24	3
B6-	1.12	5.00	1.30	5.80	6.24	4
B8-	1.12	5.00	1.80	8.00	6.24	5
C5-	2.25	10.00	1.24	5.50	12.70	6
C6-	2.25	10.00	1.30	5.80	12.70	7
D12-	4.48	20.00	2.65	11.80	24.95	8
E15-	7.19	32.00	2.88	12.80	35.60	9

All values shown represent manufactured tolerances of ± 10%

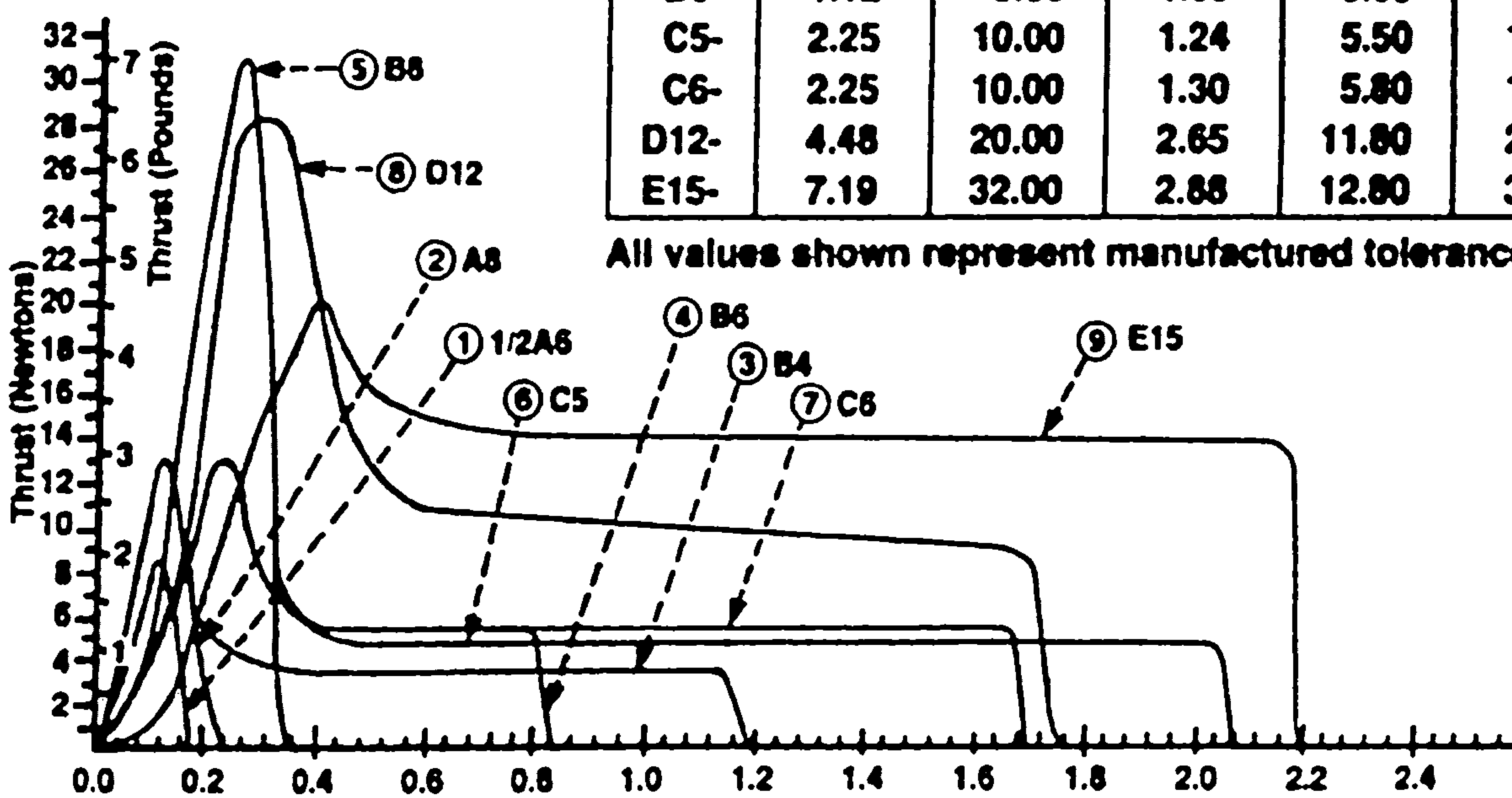


Figure A5 Estes Mini motor thrust curves

Description	Firm	Cost(£)	Use
CDB motors	RoyalOrdnance	6460.00	v
Trials rig	DKW	1460.00	c
Trials equipment	Radio Spares	1676.20	t
Centriseps	Pall Europe	6775.87	c
PSS filters	Pall Europe	587.50	c
Data aquisition board	Adept Sci	849.00	t
PSS filters	Pall Europe	250.00	c
SLR Camera	7oaks Camera	455.92	t
General equipment	Radio Spares	197.85	t
Optical fibres	Honeywell	243.39	v
PC version of PHOENICS	CHAM	2500.00	p
Ultra sonic cleaner	Cherwell labs	435.20	c
Digital scanner	Torr Group	769.75	g
Accessories for Landrover	DuttonForshaw	97.41	t
Computer upgrade	Dellware	288.00	g
Camera accessory	7oaks Camera	49.99	t
PSS filters	Pall Europe	881.25	c
Camera accessory	Radio Spares	139.80	t
Data acquisition card	Adept Sci	900.00	t
Centriseps	Pall Europe	1906.68	c
Parts for laser mount	Otford Merch	13.42	v
Rodless cylinder	Norgren	3990.50	v
Filter holders and velo stand	Cranfield	3100.00	t
Seeded motors	RoyalOrdnance	28000.00	t
CRV7 motors	Canada	1200.00	c
Parts for laser mount	Otford Merch	100.00	v
Repair of optical fibres	Honeywell	30.00	v

Table 3.1 Itemised costs - merchandise

Code	Use	Cost(£)
t	Trials equipment	35466.17
c	Collection equipment	13496.50
v	Velocity measurement	10837.31
p	Prediction code	2500.00
g	General items	1057.75
	Total (£)	63357.73

Table 3.2 Total merchandise expenditure divided into usage

Description	Firm	Cost (£)	Use
Size analysis	Malvern	300.00	c
Size analysis	MCA	225.00	c
Size analysis	MCA	112.50	c
Size analysis	Malvern	3600.00	c
Aneometer proving trial	AEA Tech	11800.00	v
Firing officer etc for above	RoyalOrdnance	10000.00	t
CRV7 particle catching trial	RoyalOrdnance	6000.00	c
Aneomometer calibration trial	AEA Tech	6900.00	v
Facilities for above	Cranfield	2769.00	v
Firing officer for seeded signature	RoyalOrdnance	4185.00	s
Aneomometer profile trial	AEA Tech	18500.00	v
Firing officer etc for above	RoyalOrdnance	11605.87	v
PhD course fees	Cranfield	7800.00	pf
Training course fees	Various	2500.00	f

Table 3.3 Itemised costs - research/trials work

Code	Use	Cost(£)
c	Collection work	10237.50
v	Velocity measurement	51574.87
t	Combined trial	10000.00
s	Signature only trial	4185.00
f	Course fees	2500.00
pf	PhD fees	7800.00
	Total (£)	86297.37

Table 3.4 Total research/trials work by type

Name	Time[1]	Rate[2]	Sub total
C.W.Dennis	4335	31.00	134385.00
R.E.Lawrence	350	40.00	14000.00
G.A.Jones	70	57.00	3990.00
M.Baker[3]	100	40.00	4000.00
		Total (£)	156375.00

[1] Approximate hours
[2] Charge out rate, £/hour
[3] Mr M.Baker performed the SEM analysis

Table 3.5 Man power effort

Expenditure type	Cost (£)
Merchandise	63357.73
Research work	86297.37
Man power effort	156375.00
Total (£)	306030.10

Table 3.6 Total expenditure

Use	Cost (£)	Percentage of total
Velocity measurement	147695.27	48.5%
Particle collection	109017.09	35.5%
Computer code	33775.00	11.0%
PhD fees	7800.00	2.5%
Other	7742.74	2.5%

Table 3.7 Break down of total expenditure areas

Name	Use	Percent	Particles?
Manufacturing additives			
Graphite	Coating agent	0.1	Trace (carbon)
Diethyl phthalate	Plast/safety	0-10%	No
Dioctyl phthalate	"	0-10%	No
Glycerol triacitate	"	0-10%	No
Glycerol triacetin	Plasticizer	0-10%	No
Sucrose octoacetate	"	0-10%	No
Ethyl phenyl urethanne	"	0-10%	No
Saccharose acetoisobutyrate	"	0-10%	No
Candellilia wax	Extrusion	0.5%	No
Montant wax	"	0.5%	No
Magnesium stearate etc	"	Low	Trace
Stability additives - prevent ageing			
Diethyl diphenyl urea	Stab Ads	Low	No
2-Nitrodiphenylamine	"	Low	No
N-methyl-*para*-nitro-aniline	"	Low	No
Resorcinol	"	Low	No
Trimethyoxybenzene	"	Low	No
2-methoxynaphthalene	"	Low	No
Ballistic modifiers			
Lead dibasic stearate	Ballistic	Low	Trace
Lead neutral stearate	"	Low	Trace
Lead salicylate	"	Low	Trace
Lead octoate	"	Low	Trace
Lead resorcylate	"	Low	Trace
Lead oxide	"	Low	Trace

Table 4.1 Additives for double base propellants

Continued;-

- continued			
Lead saline oxide	"	Low	Trace
Copper salicylate	"	Low	Trace
Copper octoate	"	Low	Trace
Copper oxide	"	Low	Trace
Copper chromite	"	Low	Trace
acetylene black	"	Low	Trace
Operational additives			
Zirconia	Stabilizer	0-2%	Yes
Zirconium silcate	"	0-2%	Yes
Silicon carbide	"	0-2%	Yes
Tungsten	"	0-2%	Yes
Boron carbide	"	0-2%	Yes
Silver or copper wires	Stab/rate	Low	Trace
Potassium cryolite	Suppression	0-4%	Trace
Potassium sulphate	"	0-4%	Trace
Potassium bitartratre	"	0-4%	Trace
Potassium oxalate	"	0-4%	Trace

Note - Double base propellants are a nitrocellulose and nitroglycerine mix with notable calcium impurities.
- Trace means either very few particles produced, or a trace of the element in particles with other main constituents.
- Low means percentages probably below 2% and therefore probably not a major particle contributor once burnt.

Table 4.1 Additives for double base propellants

Name	Use	Percent	Particles?
Manufacturing additives			
Trimethylol propane	Crosslinking	low	No
Toluylene`diisocyanate	"	low	No
Polyepoxide (Epon 812)	"	low	No
Trimethylaziridinyl phosphine oxide	"	low	Trace
Isophorone diisocyanate	"	low	No
Diisocytyl azelate	Plasticizer	low	No
Diisoctyl sebacate	"	Low	No
Isodecyl pelargonate	"	Low	No
Polyisobutylene	"	Low	No
Dioctl phthalate	"	Low	No
Triethanolamine	Wet/bond	0.1	No
Tri(2-methyl-1-aziridinyl) phosphine oxide, MAPO	"	0.1	Trace
Bis-isophtaloyl-1-methyl-2-aziridine, HX752	"	0.1	No
Methylamino-bis (2-methyl-1-aziridinyl)-phosphine-oxide, Methyl BAPO	"	0.1	Trace
Iron acetyl acetonate	Catalyst	Low	Trace
Copper acetyl acetonate	"	Low	Trace
Lead octoate	"	Low	Trace
Ditubyl tin dilaurate	"	Low	Trace
Lead chromate	"	Low	Trace
Triphenyl-bismuth	"	Low	Trace
Maleic anhydride	"	Low	Trace
Magnesium oxide	"	Low	Trace

Table 4.2 Additives for composite propellants

Continued;-

- continued			
Antioxidants			
Di tertiary butyl paracresol	Antioxidant	Low	No
Diamino n-phenyl-n'cyclohexyl-paraphenylene	"	Low	No
2.2. methylene bis (4-methyl-6-tertiary-butyl-phenol	"	Low	No
Ballistic modifiers			
Ferrocene	Accelerator	Low	Trace
n-Butylferocene	"	Low	Trace
Catocene (contains iron)	"	Low	Trace
Alkaline salts eg. lithium floride	Moderator	0-2%	Trace
Alkaline-earth solids	"	0-2%	Trace
Oxamide	Coolant	Low	No
Ammonium nitrate	"	Low	No
Nitroguanidine	"	Low	No
Stability additives may be added, as with double based motors.	Stabilizers	0-2%	Possible
Fuels and energetic additives			
Beryllium (very rare)	Fuel	0-10%	Yes
Magnesium (very rare)	"	0-10%	Yes
Aluminium	"	0-20%	Yes
Zirconium (high cost)	"	0-10%	Yes
HMX	Energetic	?	No

Note - Composite propellants are ammonium perchlorate, ammonium nitrate or potassium nitrate with a polybutidene based binder.
- Trace means either very few particles produced, or a trace of the element in particles with other main constituents.
- Low means at percentages probably below 2% and therefore probably not a major particle contributor once burnt.

Table 4.2 Additives for composite propellants

Firing number	Motor length	Distance downstream*
1	0.84m	5.25m
2	0.84m	3.95m
3	0.95m	3.84m
4	0.95m	5.14m
5	1.04m	5.05m
6	1.04m	5.05m
7	1.17m	4.96m
8	1.17m	4.96m
9	1.28m	4.87m
10	1.28m	4.87m

* The Centrisep was positioned on the plume's centre line

Table 5.1 Particle collection positions used during the proving trial

	Radial position (mm)	Collected weight (grams)
Firing 1 CDB (loose filters)	40	0.013
	160	0.008
	280	0.02
	400	0.002
	520	0.003
Firing 2 Zirconia 2% (loose filters)	40	0.879
	160	0.096
	280	0.0611
	400	0.0353
	520	0.0013
Firing 3 Zirconia 2% (loose filters)	40	0.1934
	160	0.0299
	280	0.1416
	400	0.0256
	520	0.0073
Firing 4 Zirconia 1%	40	1.1257
	160	0.0592
	280	0.0509
	400	0.0469
	520	0.038
Firing 5 0% seeding (contamination from previous firings)	40	0.2538
	160	0.0309
	280	0.002
	400	0.0181
	520	0.0268
Firing 6 Silicon carbide 2%	40	1.0093
	160	0.0929
	280	0.0329
	400	0.0012
	520	0.0032
Firing 7 Zirconia 1%	40	0.4511
	160	0.0876
	280	0.0998
	400	0.0014
	520	0.032

Table 5.2 Centrisep collection weights for Pointer and Heavyweight motors

C14 motors

Firing number and axial position	Radial position (mm)	Collected weight (grams)
Firing 10 2.5m from the nozzle	160 280 400 520	0.2559 0.1786 0.0212 0.0352
Firing 11 2.5m from the nozzle	80 200 320 440	0.2755 0.1701 0.1405 0.1096
Firing 13 1.5m from the nozzle	160 280 400 520	0.238 0.1261 0.0096 0.0018

C15 motors

Firing number and axial position	Radial position (mm)	Collected weight (grams)
Firing 8 1.5m from the nozzle	160 280 400 520	0.0599 0.056 0.0012 0.0001
Firing 9 2.5m from the nozzle	160 280 400 520	0.0549 0.057 0.008 0.004
Firing 12 2.5m from the nozzle	80 200 320 440	0.1535 0.0836 0.0245 0.0103

Table 5.3 Centrisep collection weights for CRV7 C14/C15 motors

1% Zirconia
Firing 4

Radial position mm	Plume area sqm	Weight collected grams	Centrisep area sqm	Particle conc grams/m2	Integral grams
0*	0			600	
40.00	0.005027	1.1257	0.001886	596.9537	3.008273
160.00	0.080425	0.0592	0.001886	31.39349	23.68813
280.00	0.246301	0.0509	0.001886	26.99204	4.842382
400.00	0.502655	0.0469	0.001886	24.87086	6.64763
520.00	0.849487	0.038	0.001886	20.15123	7.807547
		Total =			45.99
		1% of 5kg of propellant =			50.00
		Percentage collected =			91.99%

2% zirconia
Firing 2
(loose filters)

Radial position mm	Plume area sqm	Weight collected grams	Centrisep area sqm	Particle conc grams/m2	Integral grams
0*	0			500	
40.00	0.005027	0.879	0.001886	466.1298	2.428149
160.00	0.080425	0.096	0.001886	50.90837	19.49188
280.00	0.246301	0.0611	0.001886	32.40106	6.909521
400.00	0.502655	0.0353	0.001886	18.71943	6.55247
520.00	0.849487	0.0013	0.001886	0.689384	3.365798
		Total =			38.75
		2% of 5kg of propellant =			100.00
		Percentage collected =			38.75%

2% silicon carbide
Firing 6

Radial position mm	Plume area sqm	Weight collected grams	Centrisep area sqm	Particle conc grams/m2	Integral grams
0*	0			500	
40.00	0.005027	1.0093	0.001886	535.2273	2.60181
160.00	0.080425	0.0929	0.001886	49.26445	22.03482
280.00	0.246301	0.0329	0.001886	17.44672	5.532895
400.00	0.502655	0.0012	0.001886	0.636355	2.317834
520.00	0.849487	0.0032	0.001886	1.696946	0.404631
		Total =			32.89
		2% of 5kg of propellant =			100.00
		Percentage collected =			32.89%

* estimated values

Radial position = Centrisep radial position
Plume area = Area of plume inside the radial position
Weight collected = Weight collected by the Centrisep at the radial position
Centrisep area = Centrisep inlet area
Particle concentration = Weight collected by Centrisep divided by Centrisep inlet area
Integral = The average of adjacent Centrisep 'particle concentrations' multiplied by the plume area between them.

Table 5.4 Calculated Centrisep collection efficiency

Firing number	Sample code[1]	Axial position	Radial position	D(4,3) Microns	D(3,2) Microns	D(1,0) Microns	Data quality[2]
1	CDB 3	1.5m	40mm	13.51	1.37	0.14	g
1	CDB 4	1.5m	280mm	29.49	2.23	0.13	g
2	Zirc No 8	1.5m	40mm	12.64	3.59	0.08	g
2	Zirc No 9	1.5m	280mm	11.27	6.88	0.18	b
3	Zirc No 13	1.5m	40mm	18.56	4.15	0.09	g
3	Zirc No 14	1.5m	280mm	14.11	3.75	0.09	g
4	Zirc No 18	1.5m	40mm	12.29	4.57	0.09	g
4	Zirc No 19	1.5m	280mm	13.96	7.39	1.10	b
5	Zero No 22	1.5m	160mm	14.96	1.43	0.14	g
5	Zero No 23	1.5m	40mm	24.20	2.20	0.19	g
6	S C No 27	1.5m	160mm	27.33	4.74	0.09	g
6	S C No 28	1.5m	40mm	31.09	10.49	0.11	b
6	S C No 29	1.5m	280mm	29.48	10.86	0.58	b
7	Zirc No 32	1.5m	160mm	16.50	4.51	0.23	b
7	Zirc No 33	1.5m	40mm	12.66	4.09	0.11	b
7	Zirc No 34	1.5m	280mm	13.01	5.14	0.10	g
8	C15 No 2	1.5m	160mm	13.08	3.21	0.13	g
8	C15 No 4	1.5m	280mm	11.72	6.51	2.26	b
9	C15 No 7	2.5m	160mm	7.15	1.63	0.49	b
9	C15 No 8	2.5m	280mm	16.81	2.60	0.10	g
10	C14 No 15	1.5m	160mm	6.30	1.16	0.11	g
10	C14 No 16	1.5m	280mm	15.12	1.16	0.10	g
11	C14 No 10	2.5m	400mm	9.63	1.57	0.10	g
11	C14 No 11	2.5m	160mm	5.83	0.98	0.11	g
11	C14 No 12	2.5m	280mm	5.17	1.24	0.12	g
11	C14 No 13	2.5m	520mm	21.38	2.19	0.10	g
12	C15 No 18	2.5m	440mm	11.04	4.33	0.67	b
12	C15 No 19	2.5m	200mm	6.52	1.86	0.14	g
12	C15 No 20	2.5m	80mm	9.54	1.54	0.11	g
12	C15 No 21	2.5m	320mm	26.60	2.41	0.09	g
13	C14 No 22	2.5m	440mm	3.69	1.19	0.12	g
13	C14 No 23	2.5m	200mm	3.38	0.96	0.11	g
13	C14 No 24	2.5m	80mm	12.28	1.11	0.10	g
13	C14 No 25	2.5m	320mm	5.17	1.27	0.15	g

[1] The sample code allows traceabity back to the original samples.

[2] Assessment of size analysis

g = good
b = limitation in the measurement of the smaller sizes

Table 5.5 Collected particle D(4,3), D(3,2) and D(1,0) diameter values

Sample	D(4,3) Microns	D(3,2) Microns	D(1,0) Microns
Zirconia powder*	2.40	1.27	0.26
Silicon carbide powder*	2.95	1.71	0.18
Aluminium powder	54.39	34.87	2.12
Titanium oxide powder	0.33	0.23	0.09
CDB	13.51	1.37	0.14
Seeded - 1% zirconia	12.29	4.57	0.09
Seeded - 2% zirconia	18.56	4.15	0.09
Seeded - 2% sil carb	27.33	4.74	0.09
Seeded - no seeding	24.20	2.20	0.19
Exp Alum Comp*	5.61	2.19	0.20
CRV7 C14	12.28	1.11	0.11
CRV7 C15	9.54	1.54	0.11

* Analysis performed only down to 0.085 (not 0.05), and with lower resolution.

Table 5.6 Representitive D(4,3), D(3,2) and D(1,0) values for all particle samples

Results plotted 'by volume'

Sample	Lobe 1	Lobe 2	Min	Max
Zirconia powder*	1		0.1	10
Silicon carbide powder*	0.2	1.85	0.08	11
Aluminium powder	35		sub 1.0	200
Titanium oxide powder	0.2		sub 0.05	1.5
CDB	0.3	3	0.05	100
Seeded - 1% zirconia	0.3	6	sub 0.05	70
Seeded - 2% zirconia	0.25	4.2	sub 0.05	65
Seeded - 2% sil carb	0.17	5	sub 0.05	110
Seeded - no seeding	0.26	4.6	0.05	70
Exp Alum Comp*	0.3	5	0.085	20
CRV7 C14	0.27	3.6	0.05	17
CRV7 C15	0.25	3.2	0.05	50

Results plotted 'by number'

Sample	Lobe 1	Lobe 2	Min	Max
Zirconia powder*	0.2		0.1	2
Silicon carbide powder*	0.14		sub 0.085	1.6
Aluminium powder	sub 1.0		sub 1.0	25
Titanium oxide powder	0.08		sub 0.05	0.5
CDB	0.1		sub 0.05	0.8
Seeded - 1% zirconia	0.07		sub 0.05	0.7
Seeded - 2% zirconia	0.07		sub 0.05	0.55
Seeded - 2% sil carb	0.09		sub 0.05	0.45
Seeded - no seeding	0.12		sub 0.05	0.75
Exp Alum Comp*	0.14		0.085	0.9
CRV7 C14	0.1		sub 0.05	0.7
CRV7 C15	0.1		sub 0.05	0.6

* Analysis performed only down to 0.085 (not 0.05), and with lower resolution.
All values in microns

Table 5.7 Particle size distribution lobes and observable min and max values

Materials Characterisation Job Ref:	MP-95-066	Page Number:	1 of 1
Materials Characterisation Sample Ref:	A.981	Originators Sample Ref:	Zirconia

X - Ray Diffraction Results

1. Data

Sample A.980		$Ca_{0.15}Zr_{0.85}O_{1.85}$ Card No: 26 - 341		ZrO_2 Card No: 37 - 1484	
d (Å)	I/I_0	d (Å)	I/I_0	d (Å)	I/I_0
3.28	1				
3.17	2			3.17	100
2.97	100	2.96	100		
2.85	1			2.84	68
2.57	19	2.57	20	2.54	13
2.22	1			2.22	12
1.82	49	1.82	45		
1.69	1			1.69	11
1.65	1			1.65	11
1.55	29	1.55	25	1.55	8
1.48	6	1.48	4	1.48	8
1.28	4	1.28	4		
1.18	8	1.18	6		
1.15	4	1.15	4		
1.05	6	1.05	5		

2. Notes

The Peak at d = 3.28 Å is due to the sample holder.

N.D. Harrison

N D Harrison
Materials Characterisation Team Leader
7 November 1995

Table 5.8 XRD output table for unfired zirconia powder

Delivery angle	Collection angle	Interferometer output
45^o	45^o	0.292V
45^o	75^o	0.203V
60^o	45^o	0.203V
86^o	45^o	0.162V
86^o	127.5^o	-0.101V
127.5^o	127.5^o	-0.249V
105^o	105^o	-0.114V

Table 6.1 Interferometer output with varying delivery and collection angles

Delivery angle	Collection angle	Normalised anemometer outputs *		
		Anemometer	Equation 1 **	Equation 2 **
45^o	45^o	1.00	1.00	1.00
45^o	75^o	0.69	1.00	0.68
60^o	45^o	0.69	0.71	0.85
86^o	45^o	0.55	0.05	0.55
86^o	127.5^o	-0.34	0.05	-0.38
127.5^o	127.5^o	-0.85	-0.85	-0.86
105^o	105^o	-0.39	-0.37	-0.37

* All values are divided by the value derived with 45^0 geometry

** These are predicted anemometer outputs calculated from the velocity measured by the Pitot, Equation 1 using one Doppler shift and Equation 2 using two Doppler shifts.

Table 6.2 Comparison of the velocity derived using the two suggested equations

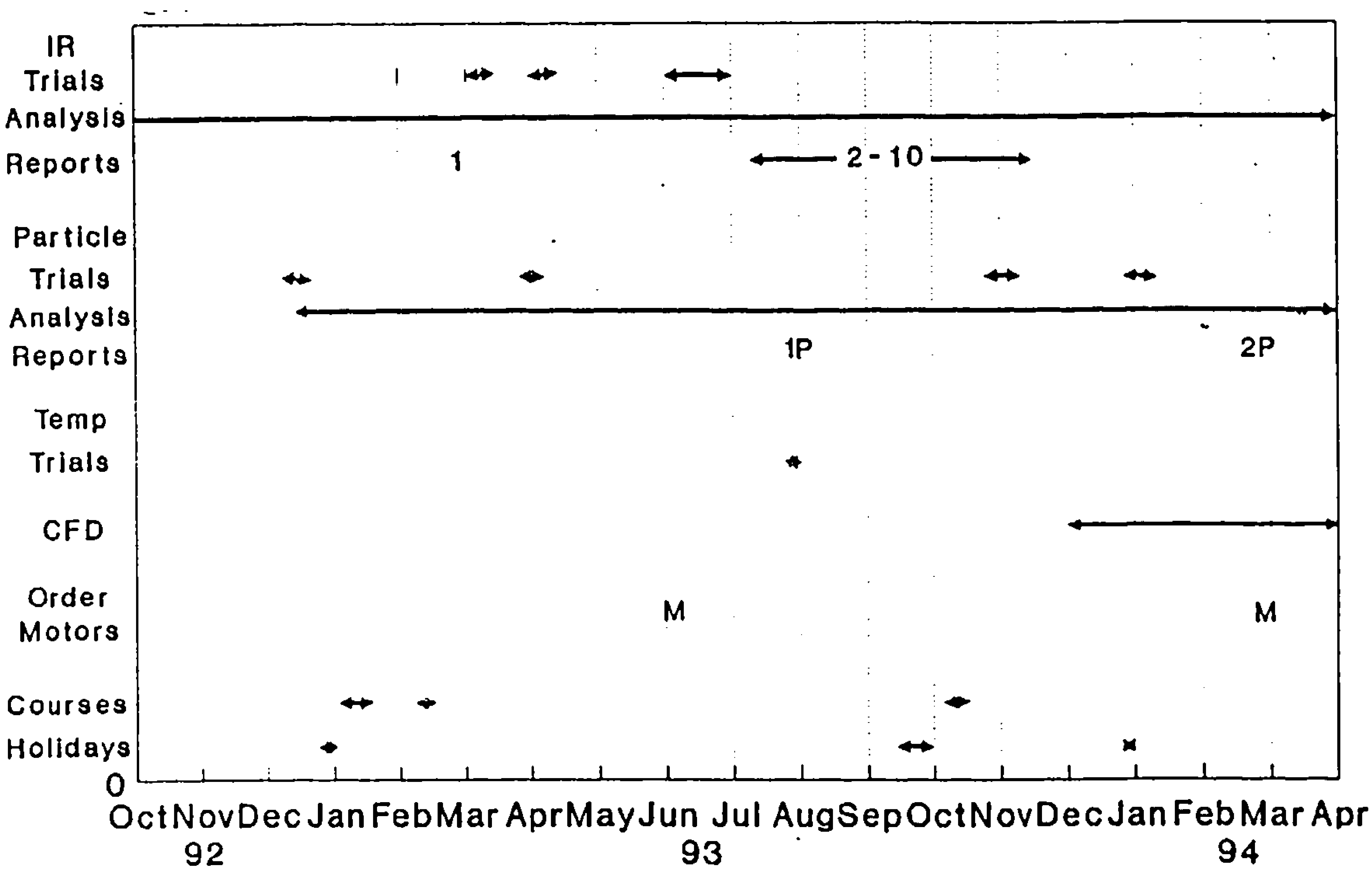
Gas temperature	Dynamic pressure	Pitot velocity	Anemometer velocity
495^0C	42.0 KPa	383 ms^{-1}	321 ms^{-1}
495^0C	42.2 KPa	385 ms^{-1}	271 ms^{-1}
595^0C	59.5 KPa	463 ms^{-1}	381 ms^{-1}
566^0C	59.7 KPa	459 ms^{-1}	457 ms^{-1}

Table 6.3 Anemometer velocities measured at elevated gas temperatures

Motor/file name	Motor	Geometry	Distance from Nozzle	Quality of data/ comments	Purpose
MINIM1/firing 1	D12-0	45° - 45°	145 mm	good	What is background level? - Both PMTs at 937V
MINIM2/firing 2	D12-0	45° - 45°	145 mm	good	Can we see a laser signal?
MINIM3/firing 3	D12-5	45° - 45°	45 mm	good	Repeat at a closer distance
MINIM4/firing 4	D12-5	45° - 45°	45 mm	good	Checking reproducibility
MINIM5/firing 5	D12-5	60° - 60°	45 mm	good	Can we collect data using 60 degree geometry, cf Heavyweight motor 5?
MINIM6/firing 6	C6-0	45° - 45°	45 mm	good	Can we use C motor?
MINIM7/firing 7	C6-0	45° - 45°	45 mm	good	Background for 6 - i.e. laser off.
MINIM8/firing 8	C6-0	45° - 45°	45 mm	did not roll over	Roll over 1 - set-up similar to firing 6
MINIM9/firing 9	C6-0	45° - 45°	45 mm	did not roll over	Roll over 2 - repeat of firing 8
MINIM10/firing 10	C6-0	45° - 45°	45 mm	did not roll over	Roll over 3 - repeat of firing 9 but with 15% transmission filter in front of the collection fibre
MINIM11/firing 11	C6-0	45° - 45°	45 mm	good	Reproducibility - aiming to repeat firing 6
MINIM12/firing 12	C6-0	30° - 30°	45 mm	did not roll over	Roll over 4 - now at 30 degree geometry to reduce dynamic range by further 22%
MINIM13/firing 13	C6-0	30° - 30°	45 mm	did not track	What velocities are present at this geometry
MINIM14/firing 14	C6-0	30° - 30°	45 mm	good	Background for 12&13 - i.e. laser off
MINIM15/firing 15	C6-0	45° - 45°	45 mm	good	Background for C motor at 45 degree geometry
MINIM16/firing 16	D12-5	45° - 45°	18 mm	good	Trying to get a higher velocity flow
MINIM17/firing 17	D12-5	45° - 45°	18 mm	did not roll over	Roll over 5 - using flow as per firing 16
MINIM18/firing 18	D12-5	60° - 60°	45 mm	poor - light level too high	Start of plume mapping
MINIM19/firing 19	D12-3	60° - 60°	45 mm	good	Repeat of firing 18 with 15% transmission filter in front of the collection fibre & PMT at 900V
MINIM20/firing 20	D12-3	60° - 60°	95 mm	good	Plume mapping - PMT back to 900V, 15% filter in
MINIM21/firing 21	D12-5	60° - 60°	145 mm	good	Plume mapping - 45% transmission filter in
MINIM22/firing 22	D12-5	60° - 60°	195 mm	good	Plume mapping - 45% transmission filter in
MINIM23/firing 23	D12-5	60° - 60°	70 mm	good	Plume mapping - 15% transmission filter in
MINIM24/firing 24	D12-5	60° - 60°	20 mm	good	Plume mapping - 15% transmission filter in
MINIM25/firing 25	D12-0	60° - 60°	20 mm	good	Repeat of firing 24 - - 45% transmission filter in
MINIM26/firing 26	D12-0	60° - 60°	20 mm	did not roll over	Roll over 6 - cf firing 24 & 25 - 15% transmission filter in
MINIM27/firing 27	D12-0	60° - 60°	32.5 mm	good	Plume mapping - 15% transmission filter in
MINIM28/firing 28	D12-0	60° - 60°	45 mm	no data	Plume mapping - 1 cm to the side, - 15% transmission filter in
MINIM29/firing 29	D12-0	60° - 60°	45 mm	failed to track	repeat of 28 - but with 15% transmission filter removed
MINIM30/firing 30	D12-0	60° - 60°	45 mm	good	Plume mapping - 0.5 cm to the side, - 15% transmission filter in
MINIM31/firing 31	D12-5	45° - 45°	18 mm	It did roll over!	Final attempt to get it to roll over (try 7)
MINIM32/firing 32	D12-0	45° - 45°	18 mm	It did roll over	Roll over 8 - repeat of firing 31

Table 6.4 Summary of collected data from the Mini motors

WORK TIMETABLE - PART 1



WORK TIMETABLE - PART 2

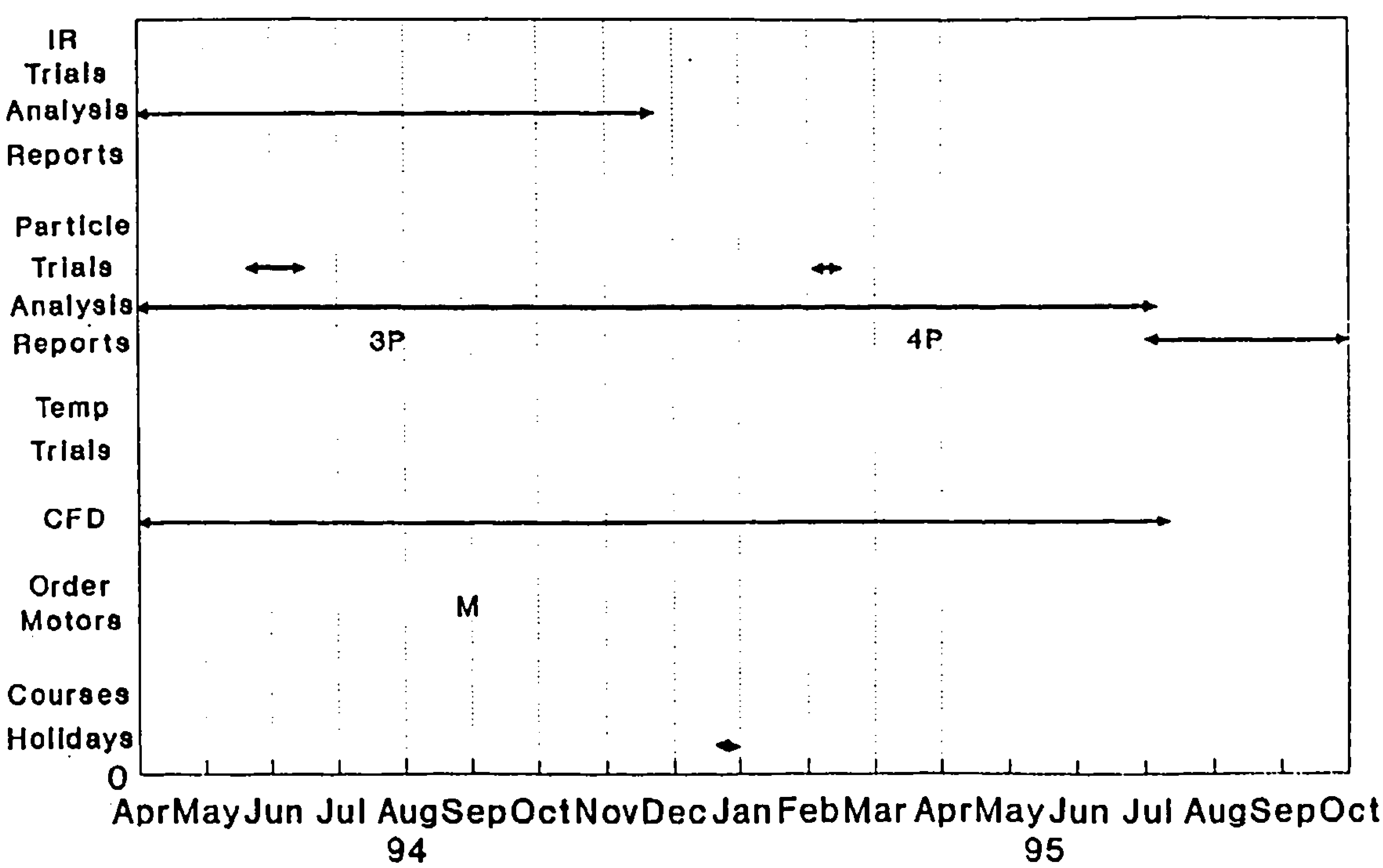


Figure 2.1 Timetable of PhD as of Dec 1992 (Reduced to 50%)

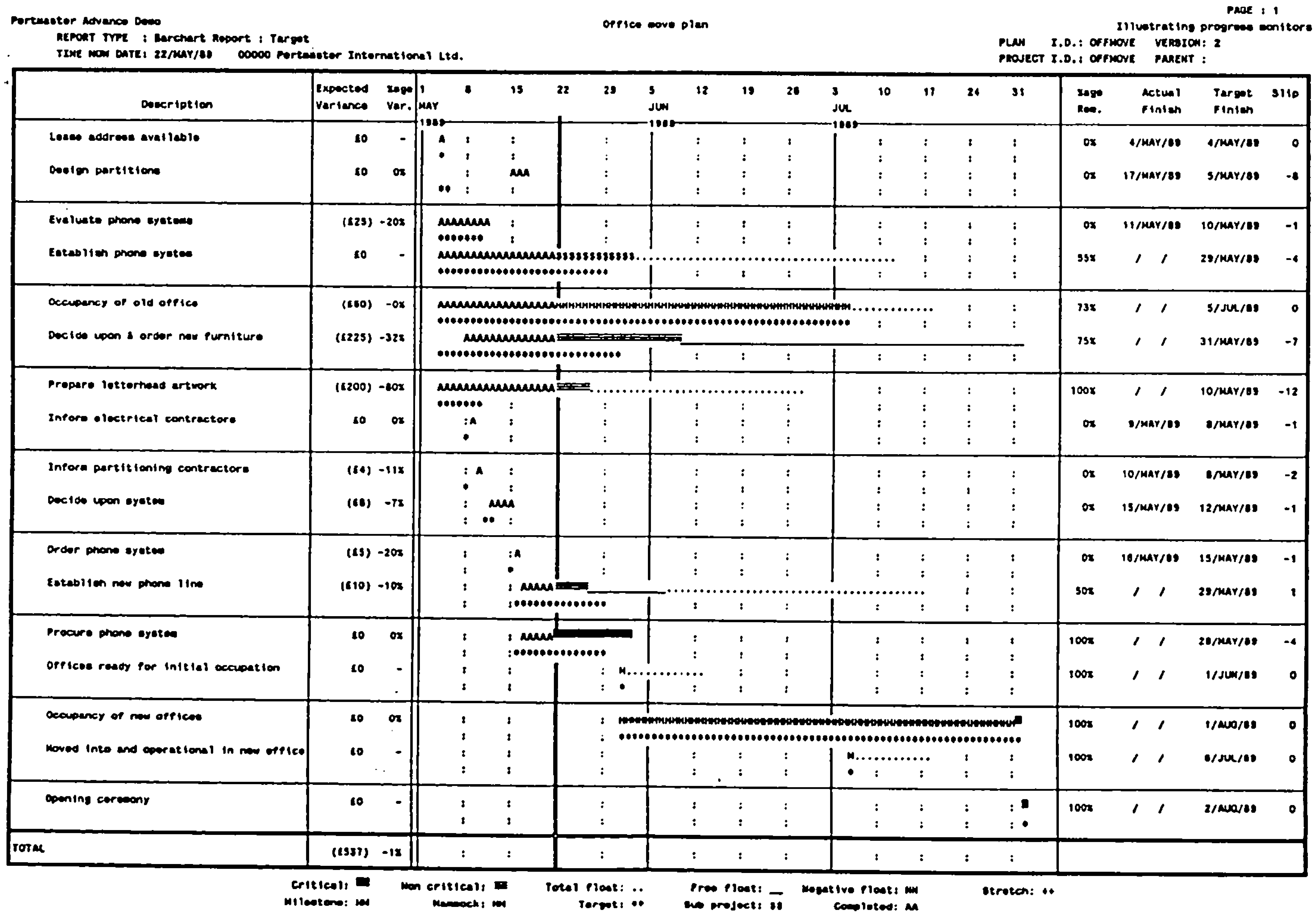


Figure 2.2 Pertmaster Gantt chart of imaginary project (Reduced to 50%)

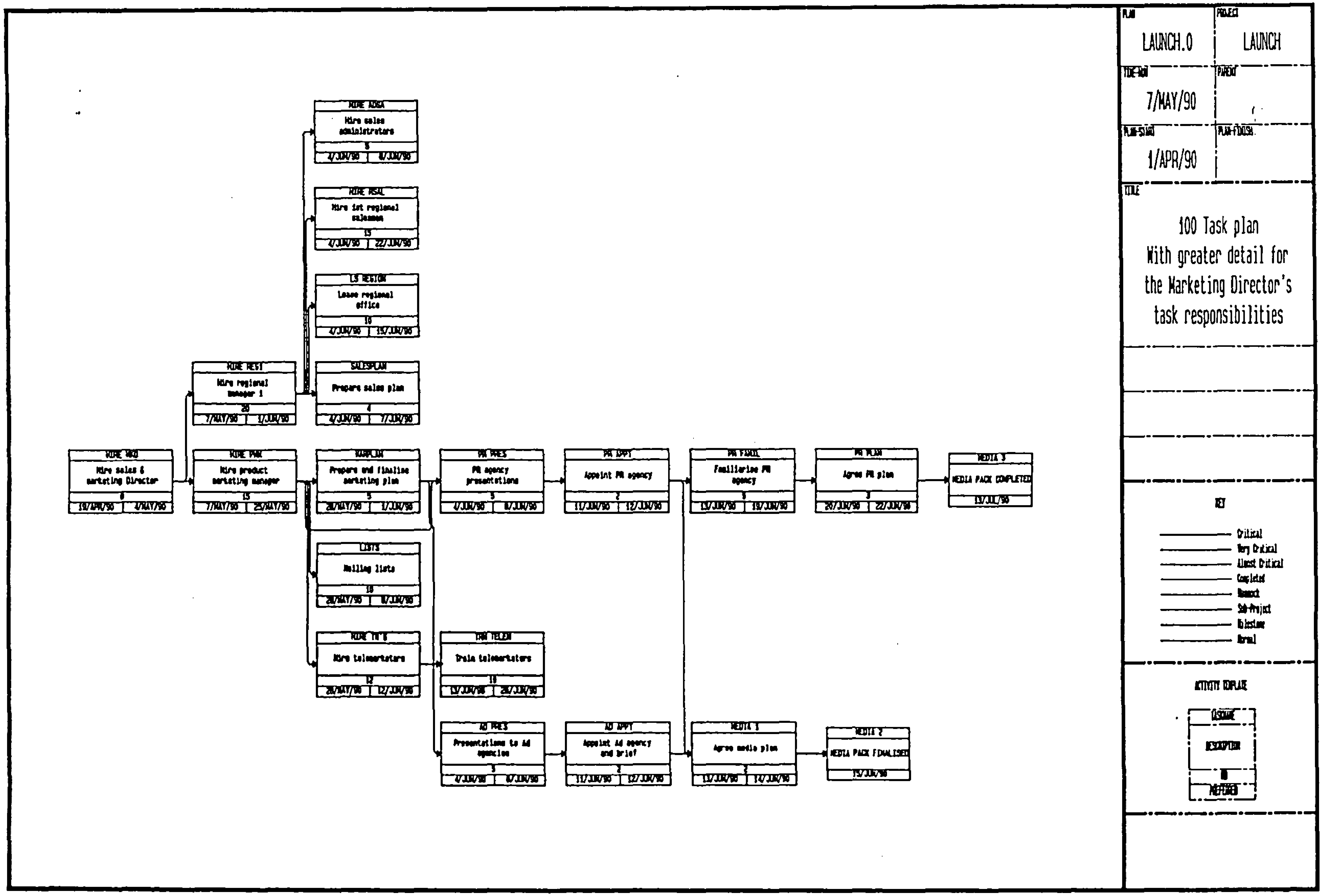
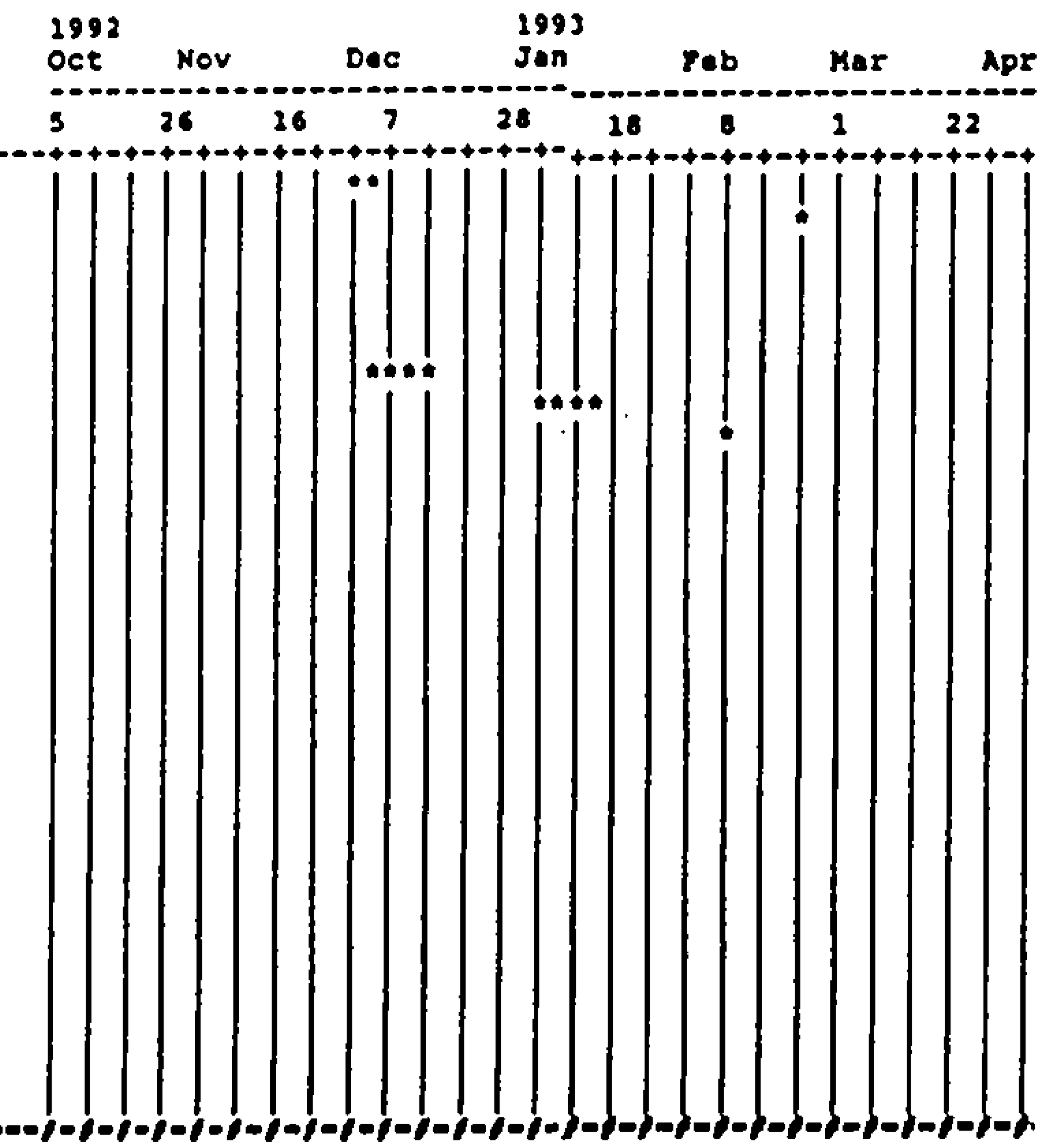


Figure 2.3 Pertmaster PERT chart of imaginary project (Reduced to 50%)

Date: 10-Feb-94
Time Now: 10-Feb-94
Project ROCKET EXHAUST PLUME PHD
Output PhD plan
Sheet No: 1

Generation: 9

	Task	Start	Finish	Duration	Identification
PAN	PHD panel meeting	Assumed	4Dec92	0,1	------>[PHDME1]------>
	PHD panel meeting	Assumed	25Feb93	0,1	------>[PHDME2]------>
	PHD panel meeting	6Jul93	6Jul93	0,1	------>[PHDME3]------>
	PHD panel meeting	Assumed	2Nov93	0,1	------>[PHDME4]------>
	PhD panel meeting	9Feb94	9Feb94	0,1	------>[PHDME5]------>
	PhD panel meeting	8Jun94	8Jun94	0,1	------>[PHDME6]------>
CWD	Particle trial 1	5Dec92	18Dec92	2,0	------>[PATRI1]------>
	Management course	4Jan93	18Jan93	2,1	------>[MANCOU]------>
	Instrumentation course	Assumed	12Feb93	1,0	------>[INSCOU]------>
	Pre NATO trial IR	Assumed	28May93	0,4	------>[IRTR]------>
	NATO trial	Assumed	25Jun93	3,3	------>[IRTRN1]------>
	IR case temperature trial	Assumed	26Nov93	1,1	------>[IRTRC]------>
	Multi nozzle trial.	Assumed	3Dec93	1,0	------>[IRMN]------>
	Order equipment for trial two	Assumed	5Jan94	1,0	------>[ORDEQ2]------>
	Order motors for second trial	Assumed	5Jan94	0,1	------>[ORDMO2]------>
	Order equipment for temp/pressure trial	19Apr94	25Apr94	1,0	------>[ORDEQT]------>
	Deliver motors for second trial	25Apr94	25Apr94	0,1	------>[DELMO2]------>
	Delivery of equipment for second particle trial.	25Apr94	29Apr94	1,0	------>[DELEQ2]------>
	Particle trial two	18May94	24May94	1,0	------>[PATRI2]------>
	Order equipment for the third particle trial	27May94	3Jun94	1,0	------>[ORDEQ3]------>
	Order motors for the third trial.	6Jun94	6Jun94	0,1	------>[ORDMO3]------>
	Delivery of temp/pressure equipment.	5Aug94	11Aug94	1,0	------>[DELEQT]------>
	Temp/pressure trial.	30Aug94	5Sep94	1,0	------>[T/PTR]------>
	NATO trial in France	3Oct94	21Oct94	3,0	------>[IRTRN2]------>
	Deliver motors for third trial.	7Nov94	7Nov94	0,1	------>[DELMO3]------>
	Delivery of equipment for particle trial 3	7Nov94	11Nov94	1,0	------>[DELEQ3]------>
	Particle trial three.	25Nov94	1Dec94	1,0	------>[PARTR3]------>



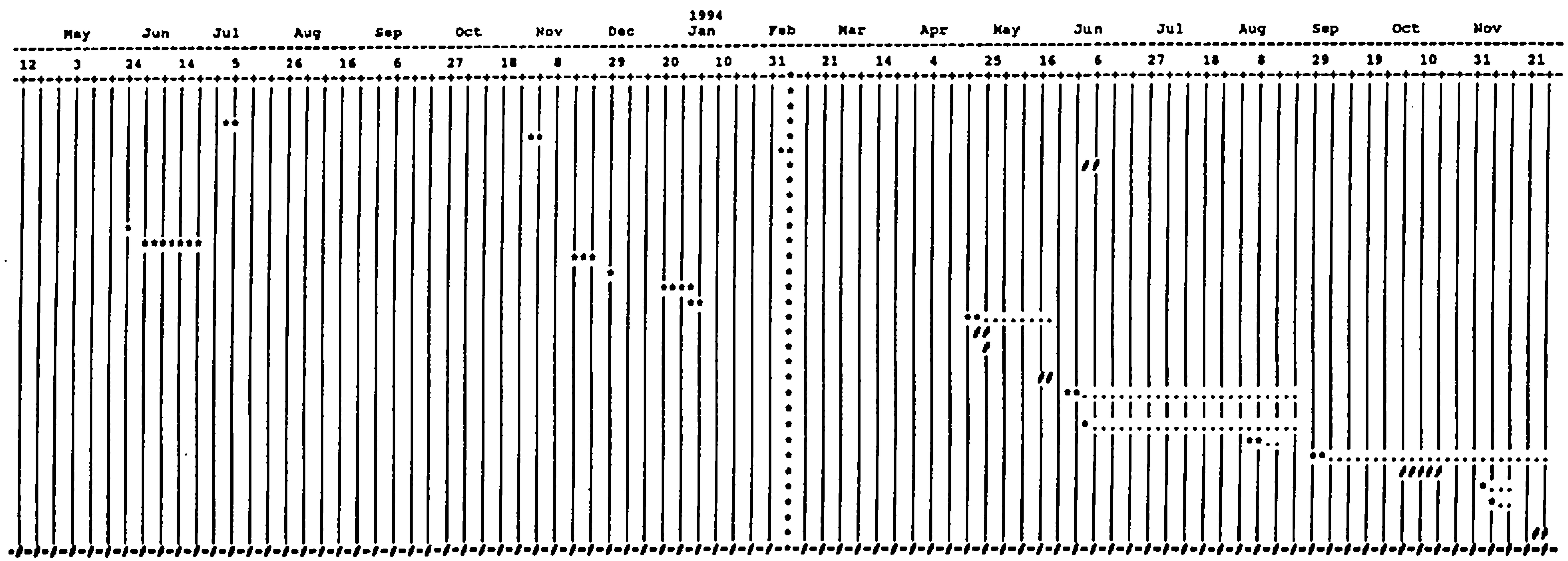
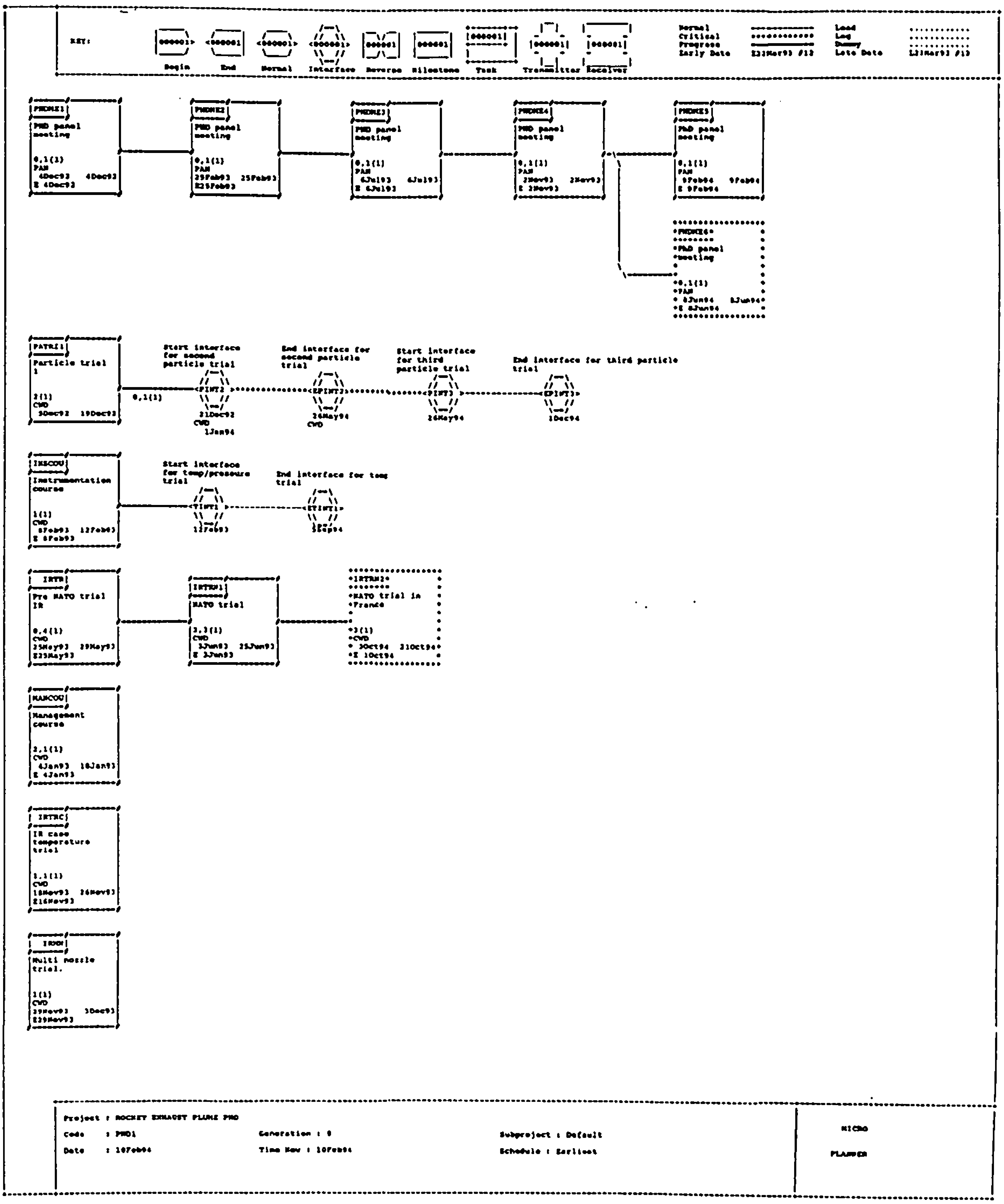


Figure 2.4 Gantt chart of PhD as of Feb 1994 (Micro Planner Professional) (Reduced to 30%)



(Reduced to 30%)

Figure 2.5 PERT chart of PhD as of Feb 1994 (Micro Planner Professional)

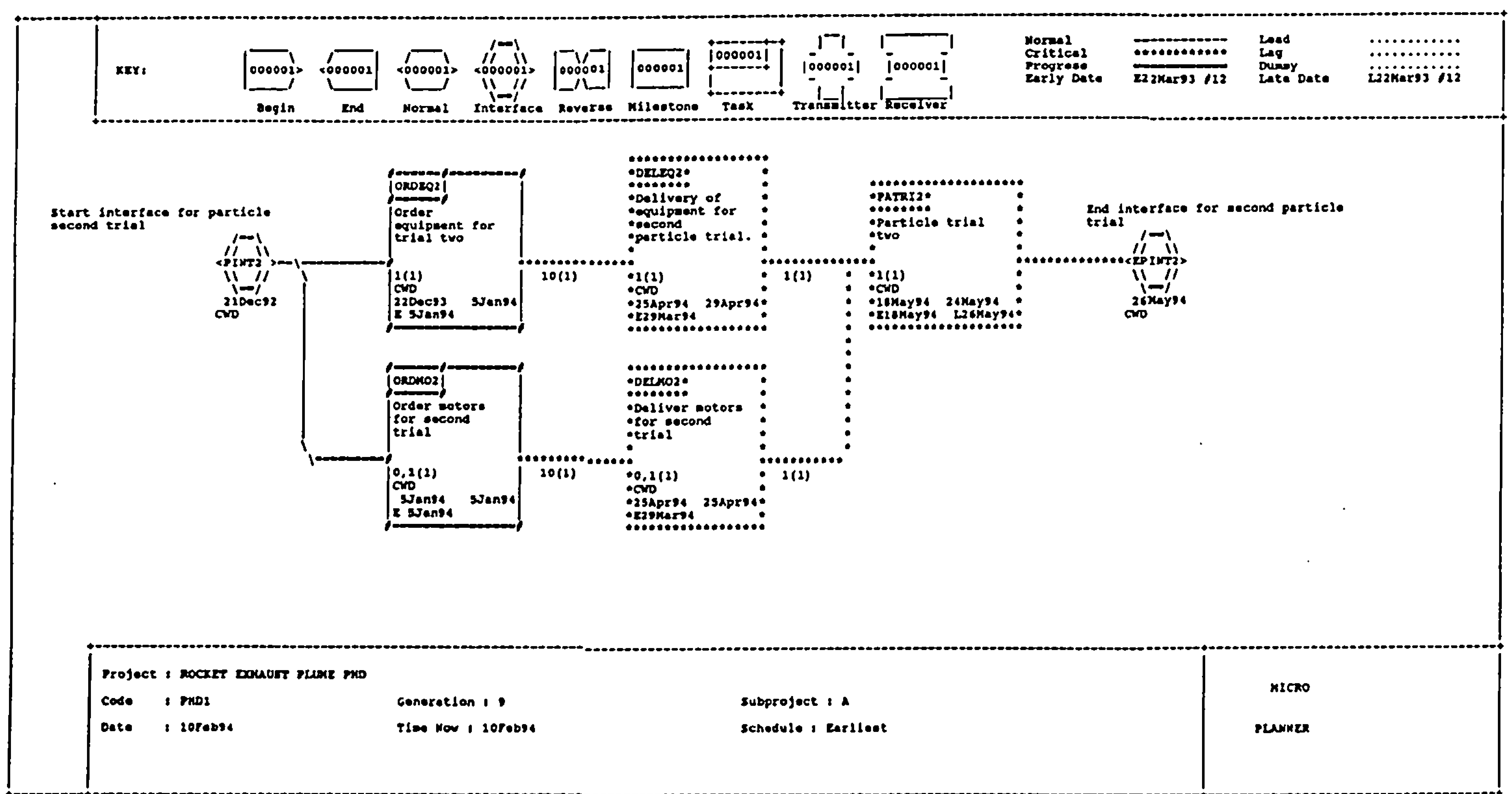


Figure 2.6 PERT chart of experimental trial (Micro Planner Professional) (Reduced to 40%)

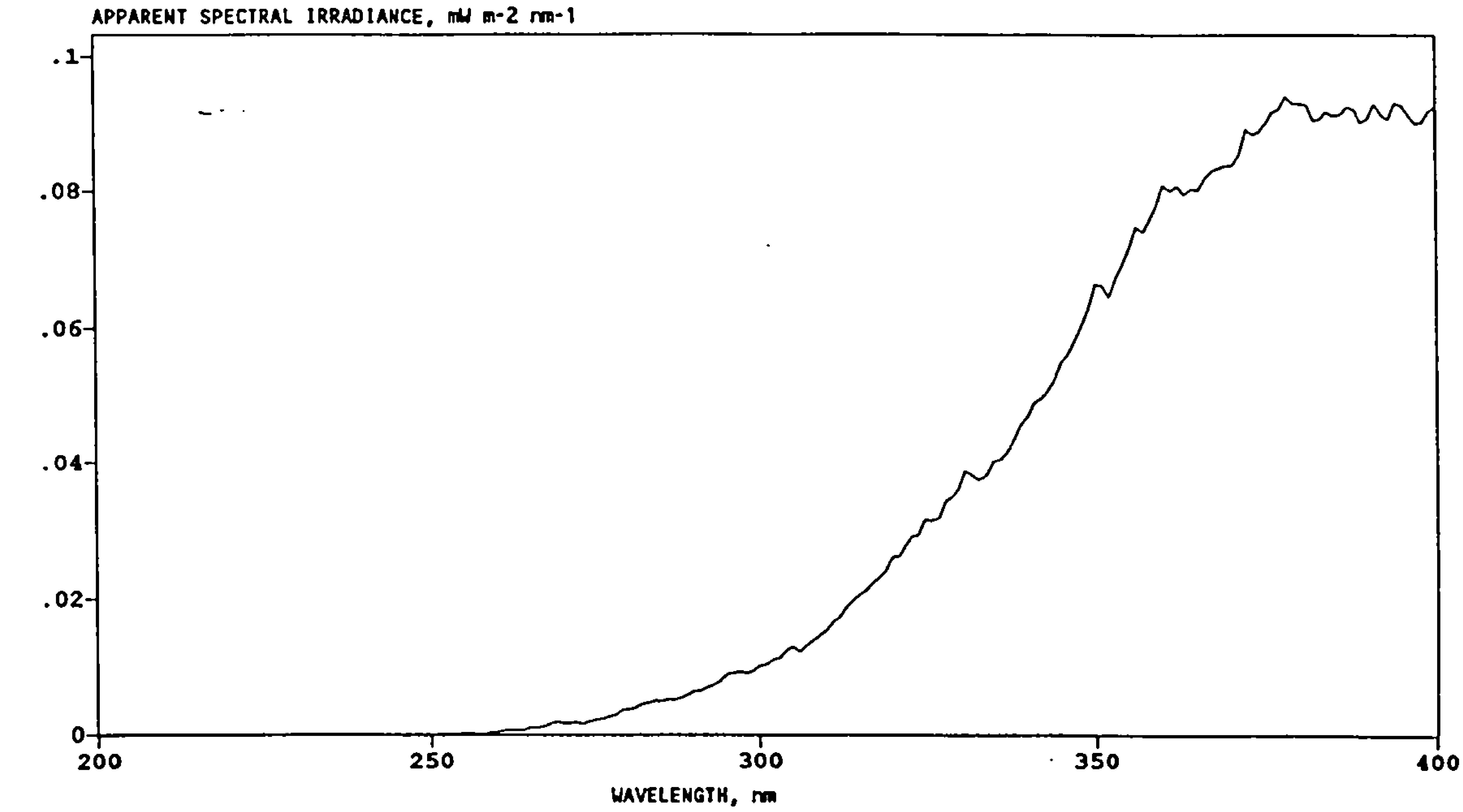


Figure 4.1 Ultraviolet waveband spectral measurement of a CRV7 C14 motor

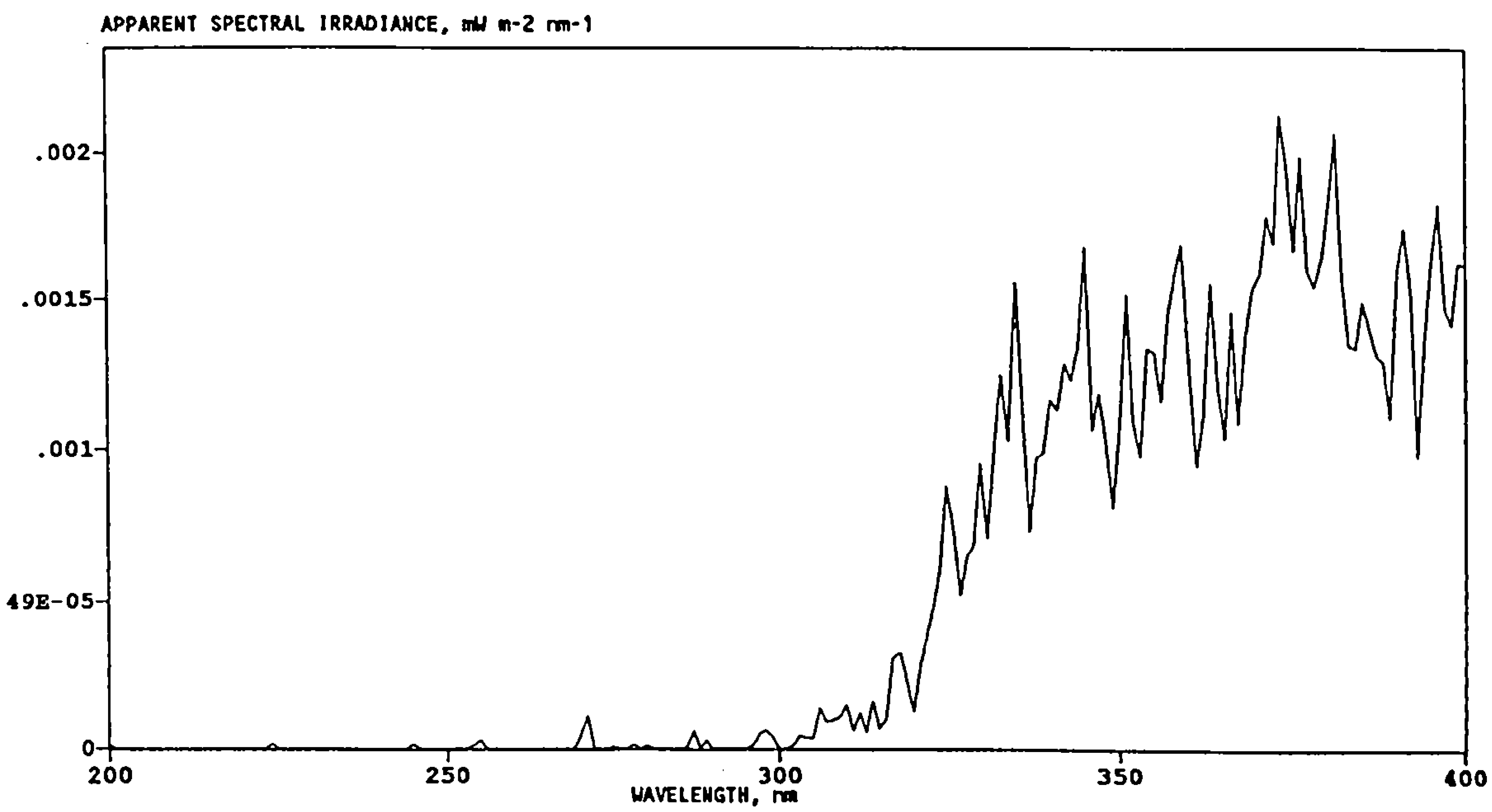


Figure 4.2 Ultraviolet waveband spectral measurement of a CRV7 C15 motor

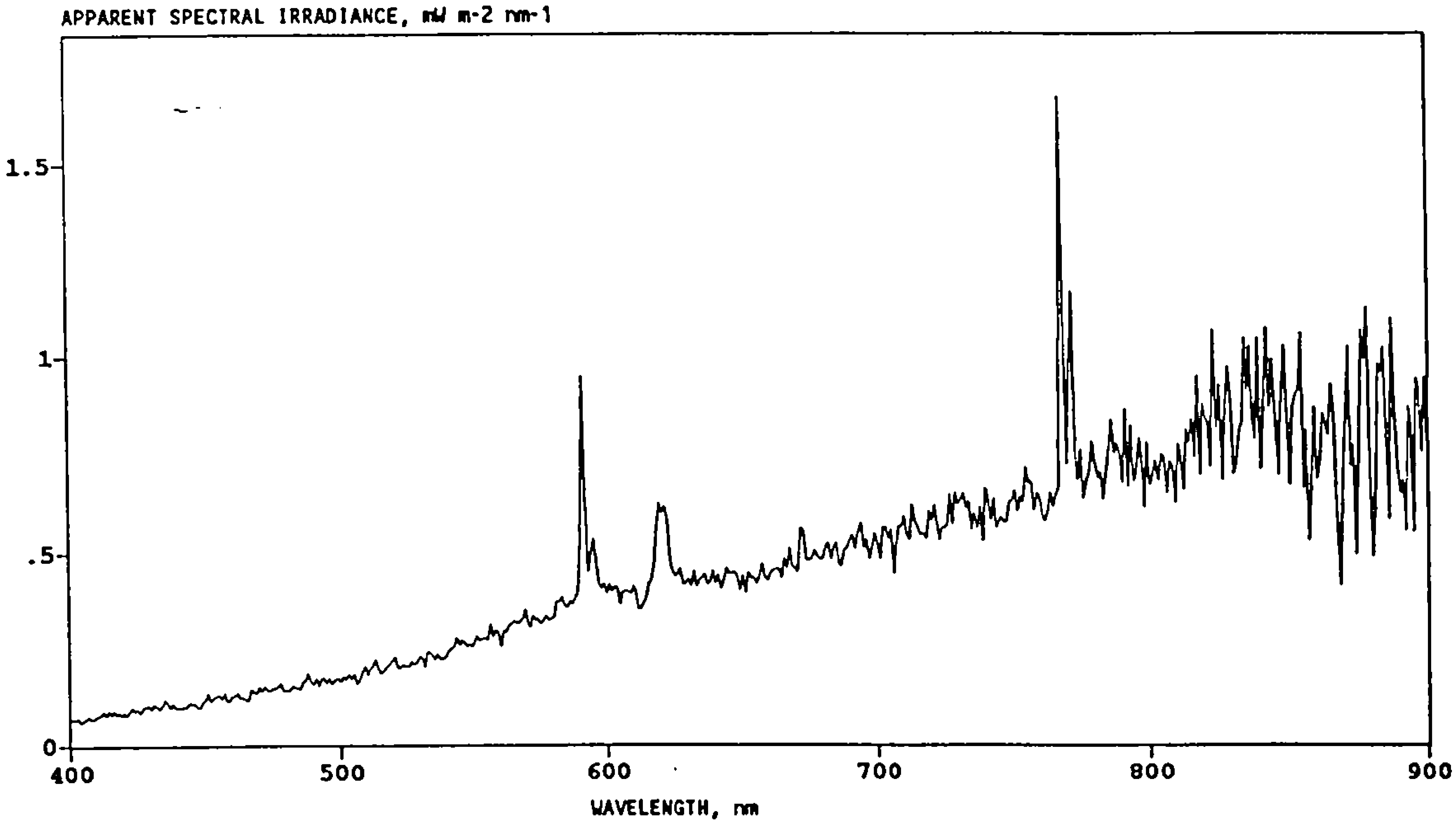


Figure 4.3 Visible waveband spectral measurement of a CRV7 C14

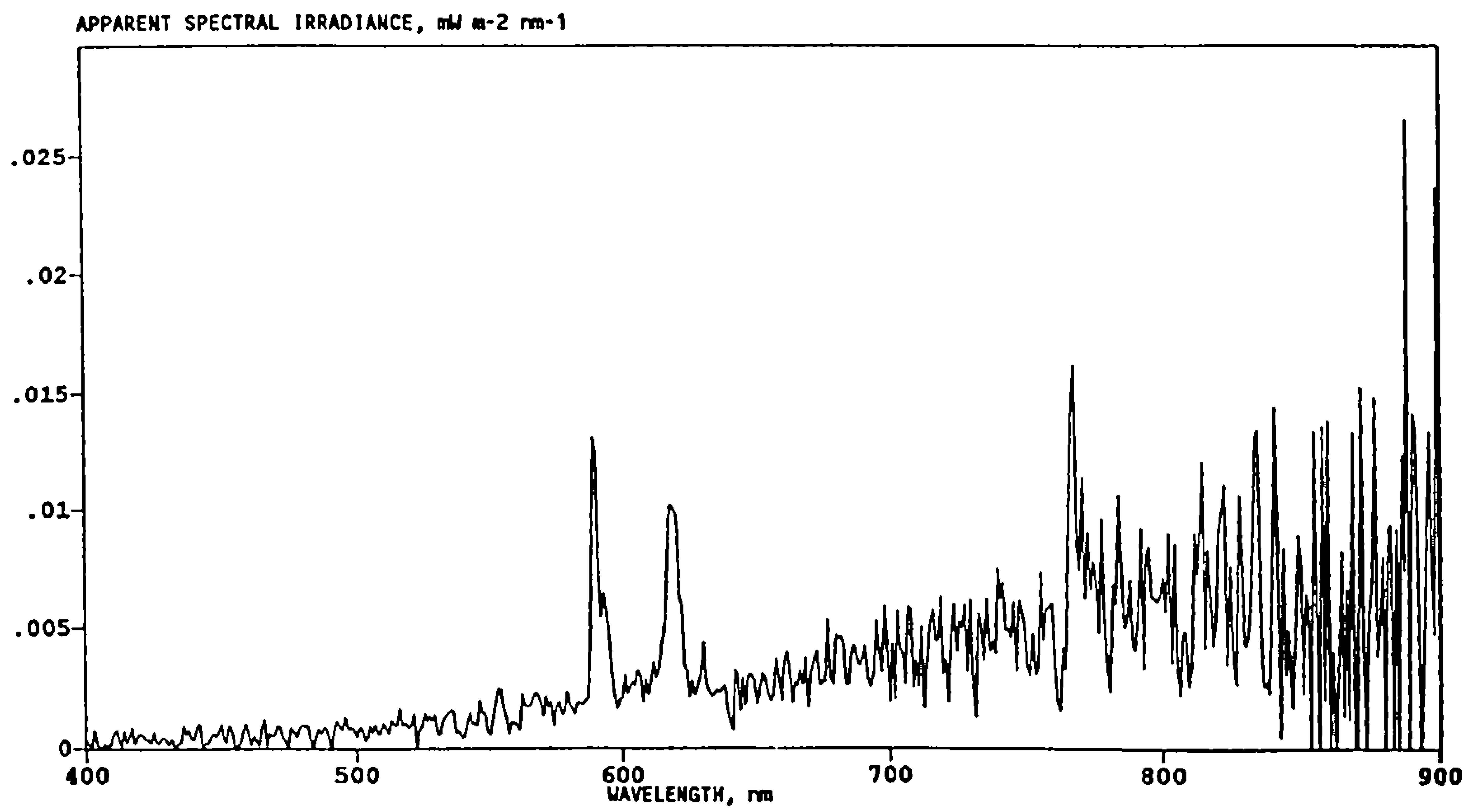
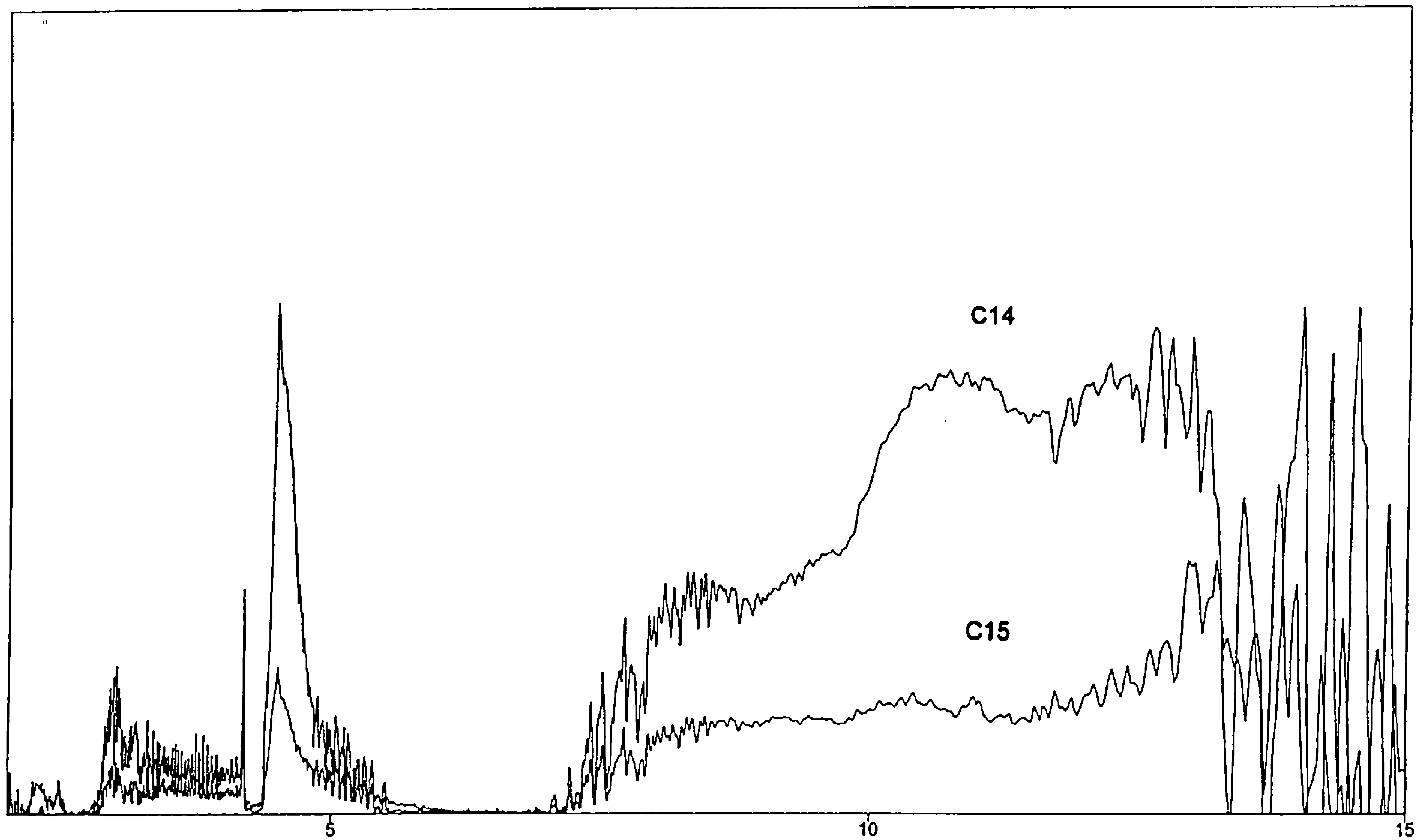


Figure 4.4 Visible waveband spectral measurement of a CRV7 C15 motor



Relative irradiance against wavelength (microns)

Figure 4.5 Infrared waveband spectral measurements of CRV7 C14 and C15 motors

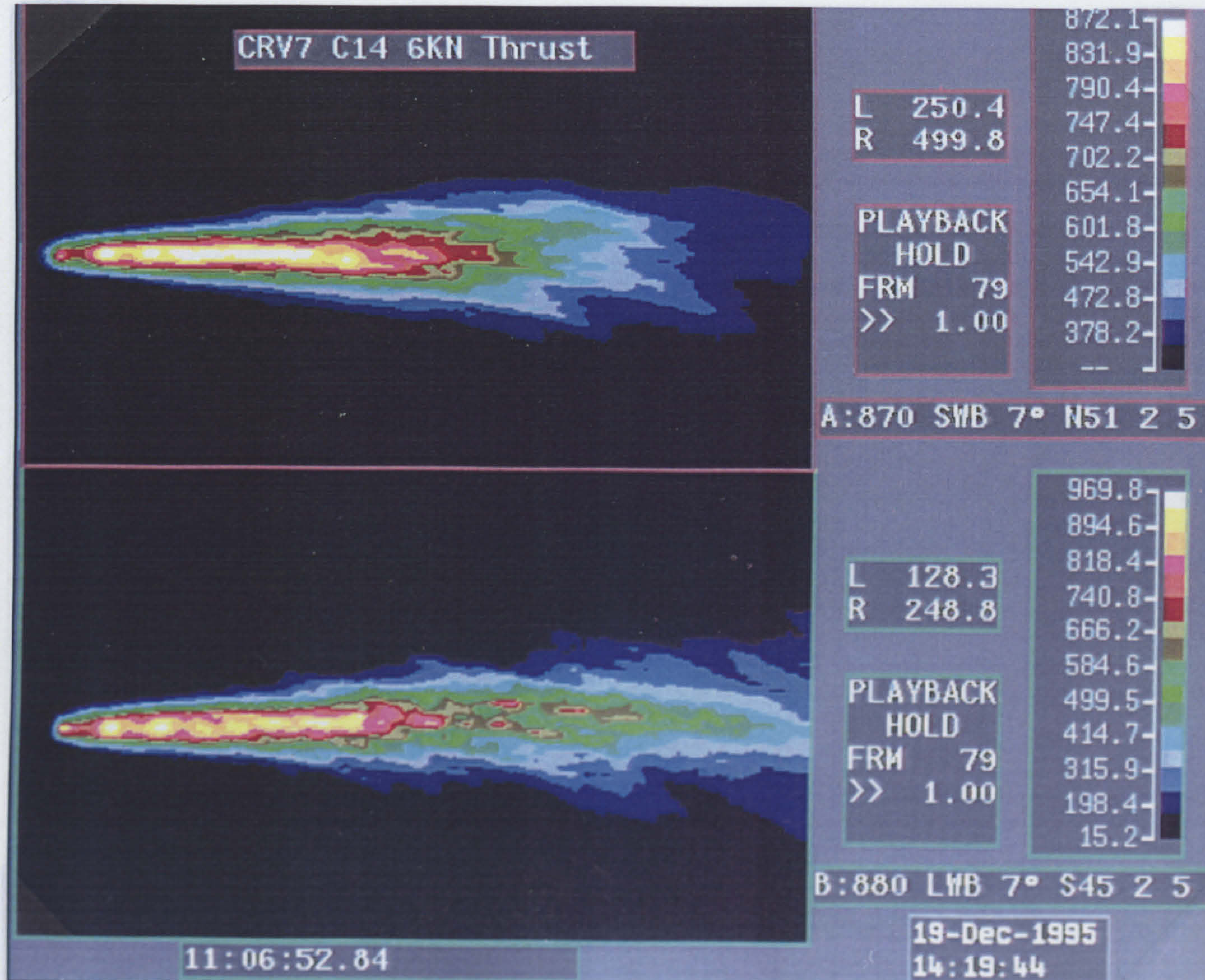


Figure 4.6 Infrared spatial measurement of CRV7 C14 motor (SWB 2.11-5.42 microns, LWB 8.11-12.36 microns)

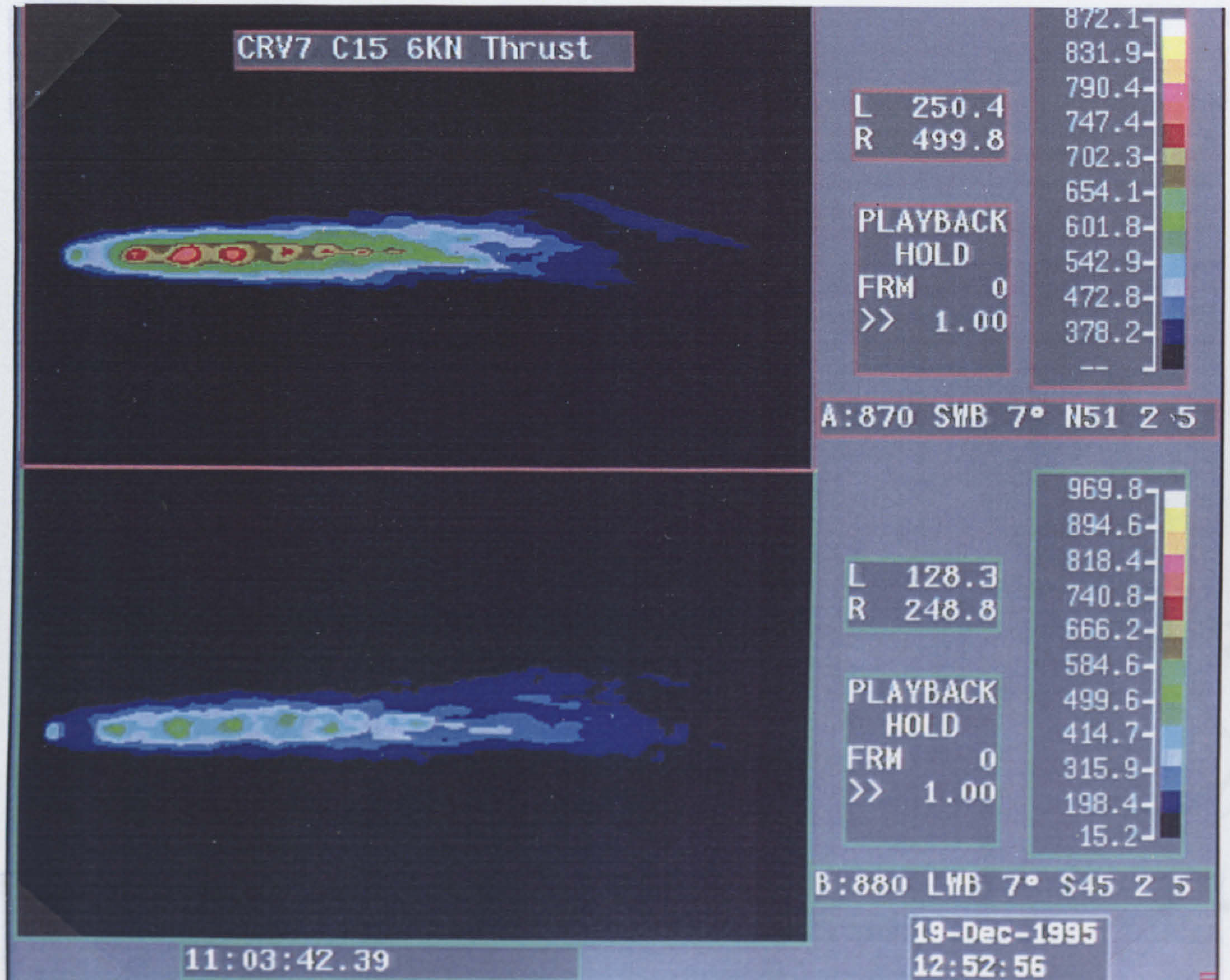


Figure 4.7 Infrared spatial measurement of CRV7 C15 motor (SWB 2.11-5.42 microns, LWB 8.11-12.36 microns)

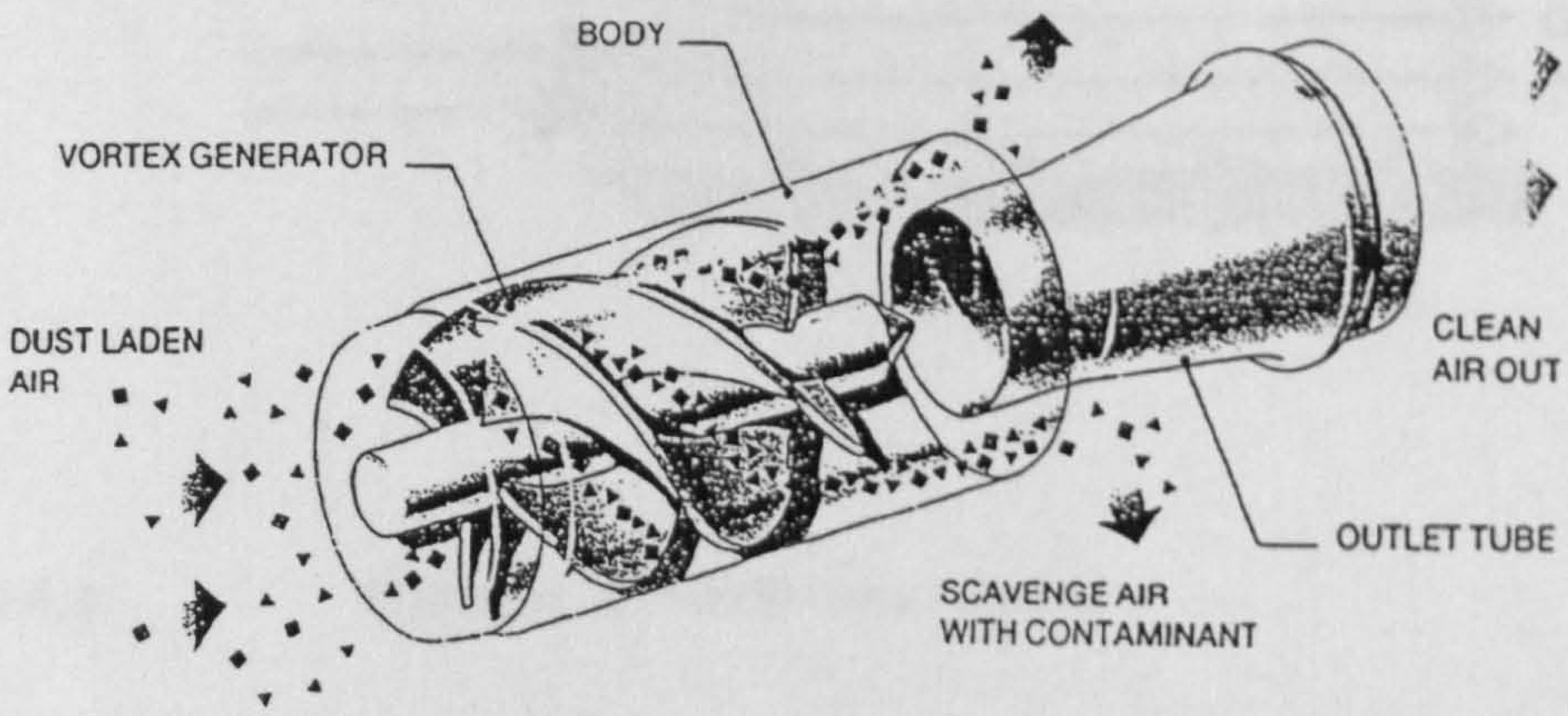


Figure 5.1 Schematic of Centrisep (centrifugal separator)

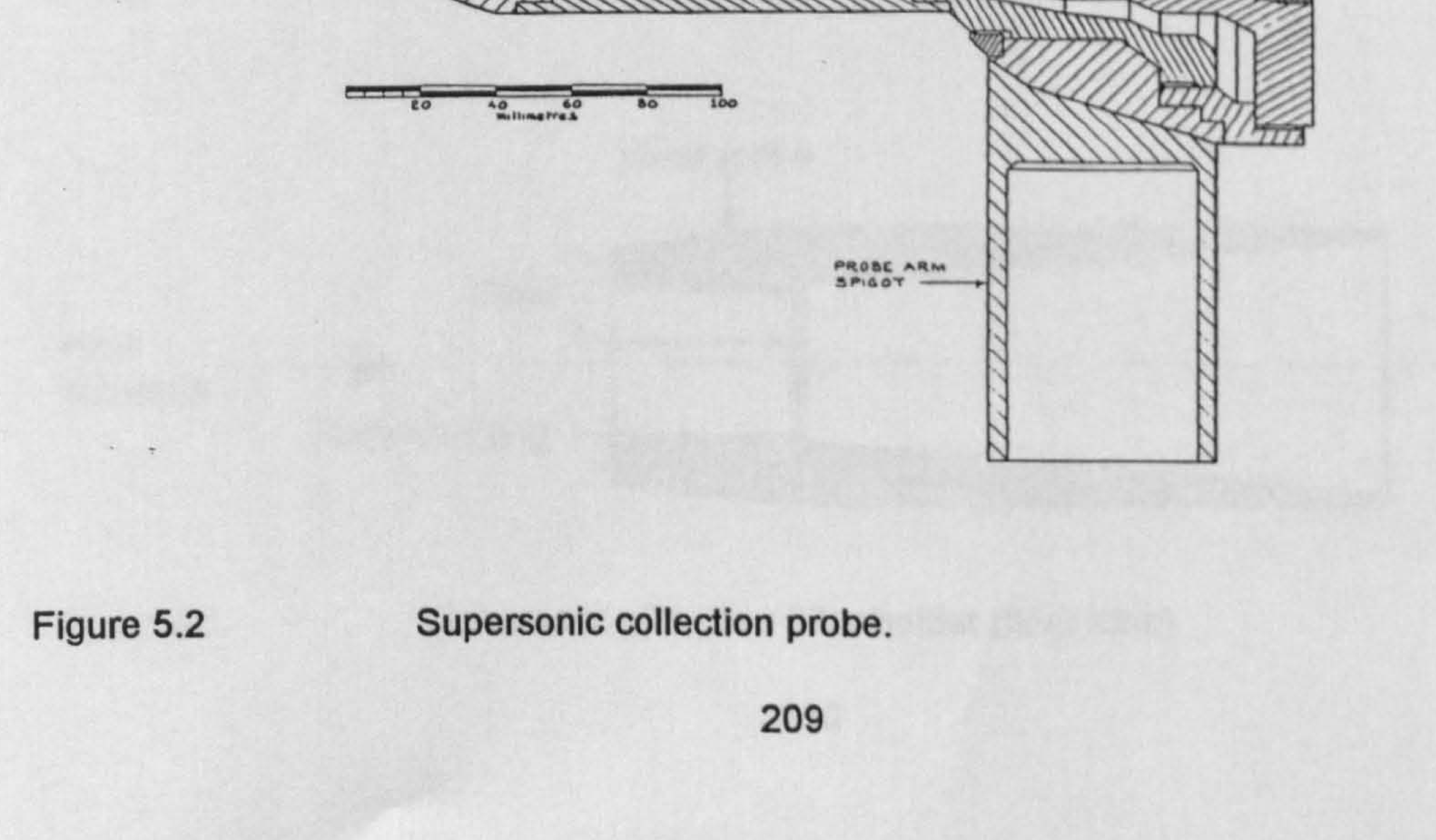


Figure 5.2 Supersonic collection probe.

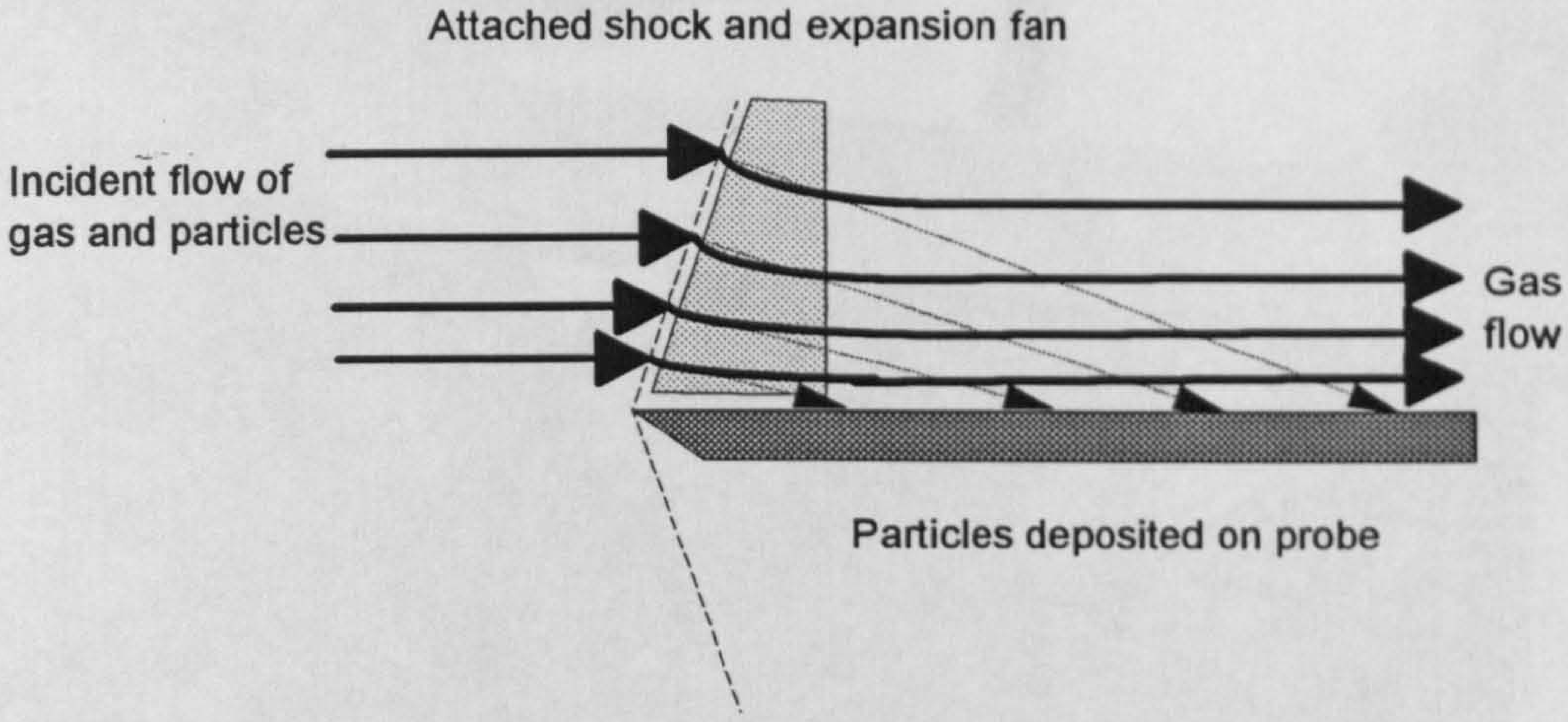


Figure 5.3 Schematic of Prandtl Meyer probe

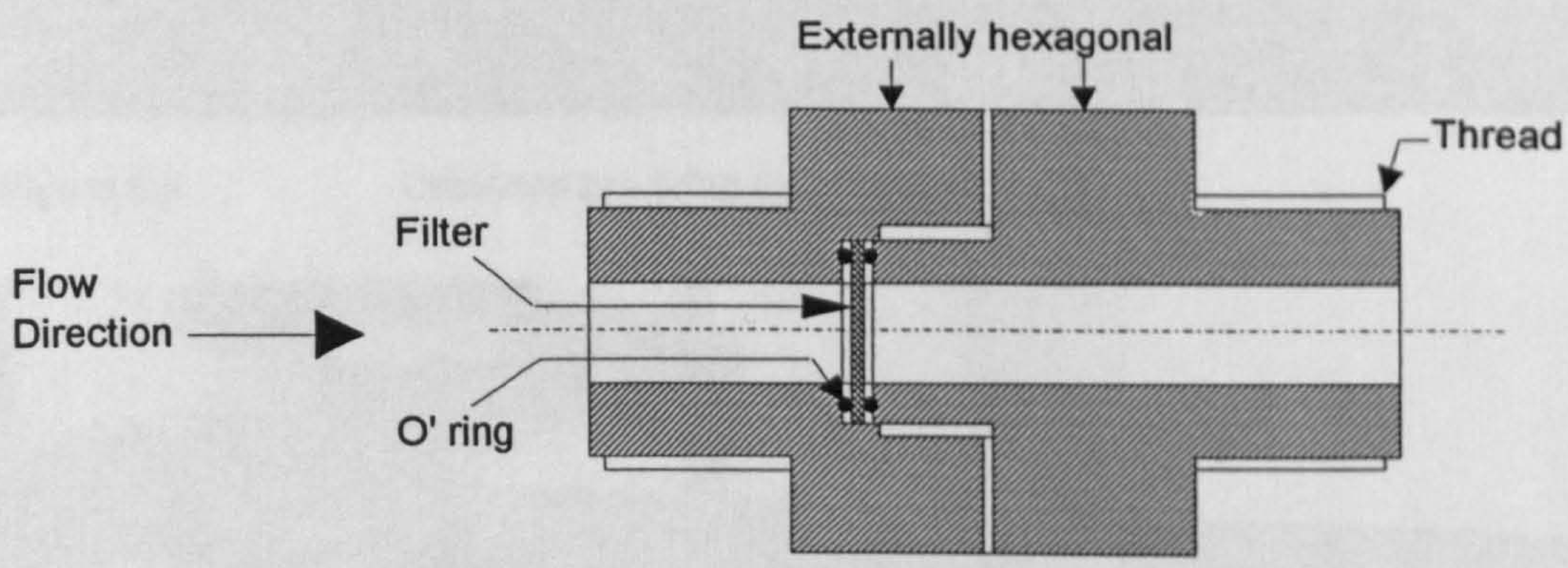


Figure 5.4 Schematic of Centrisep/in-flow filter holder (proving trial)

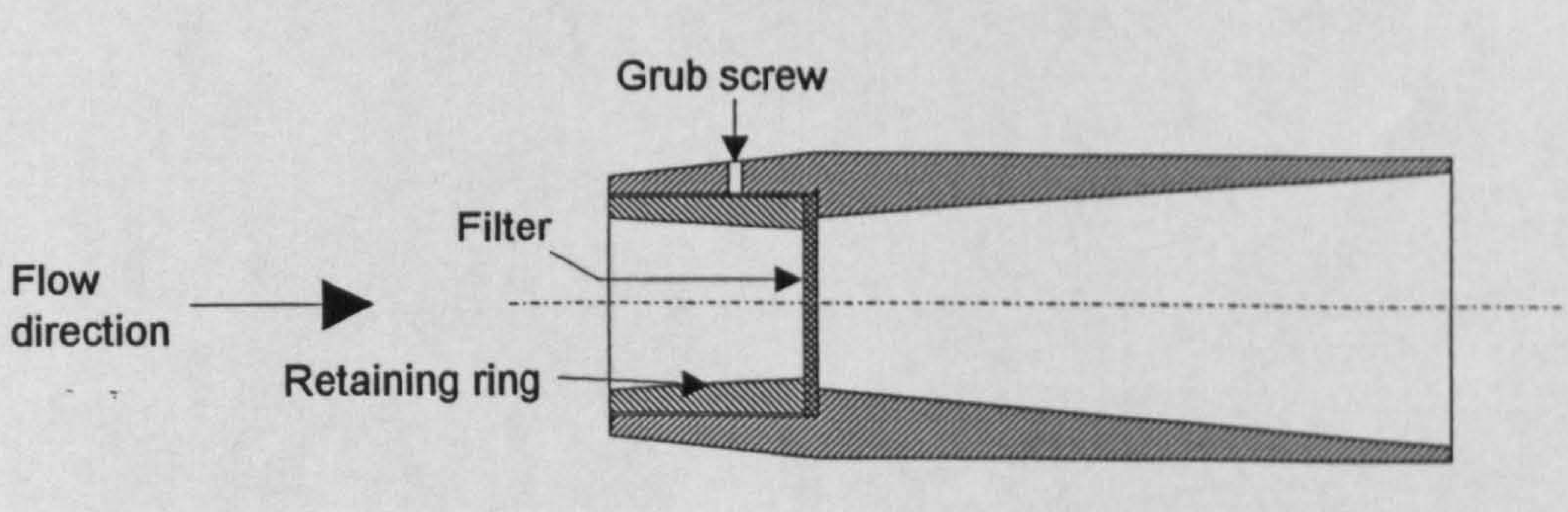


Figure 5.5 Schematic of in-flow filter holder (final form)

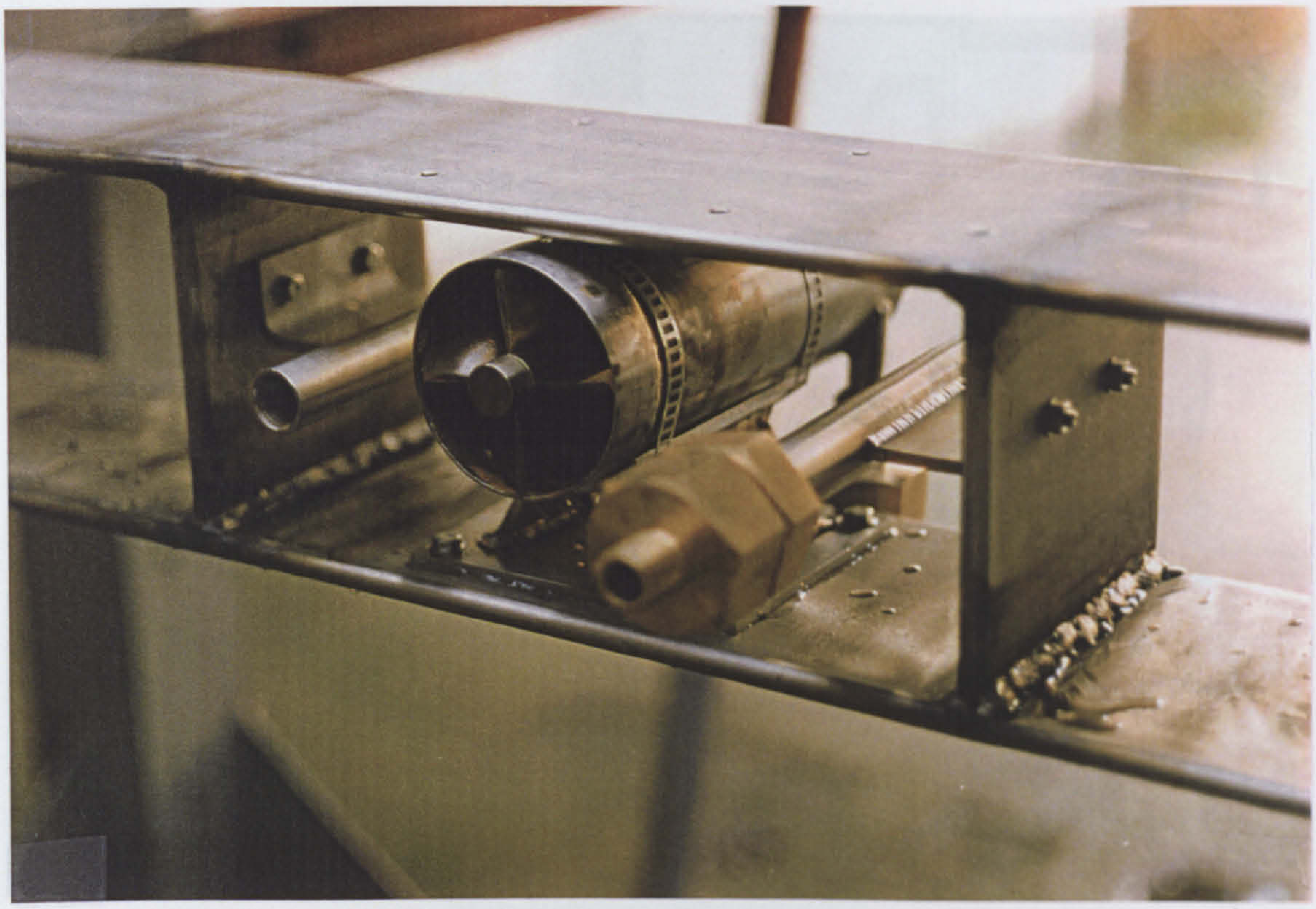


Figure 5.6 Centrisep pre firing (proving trial)

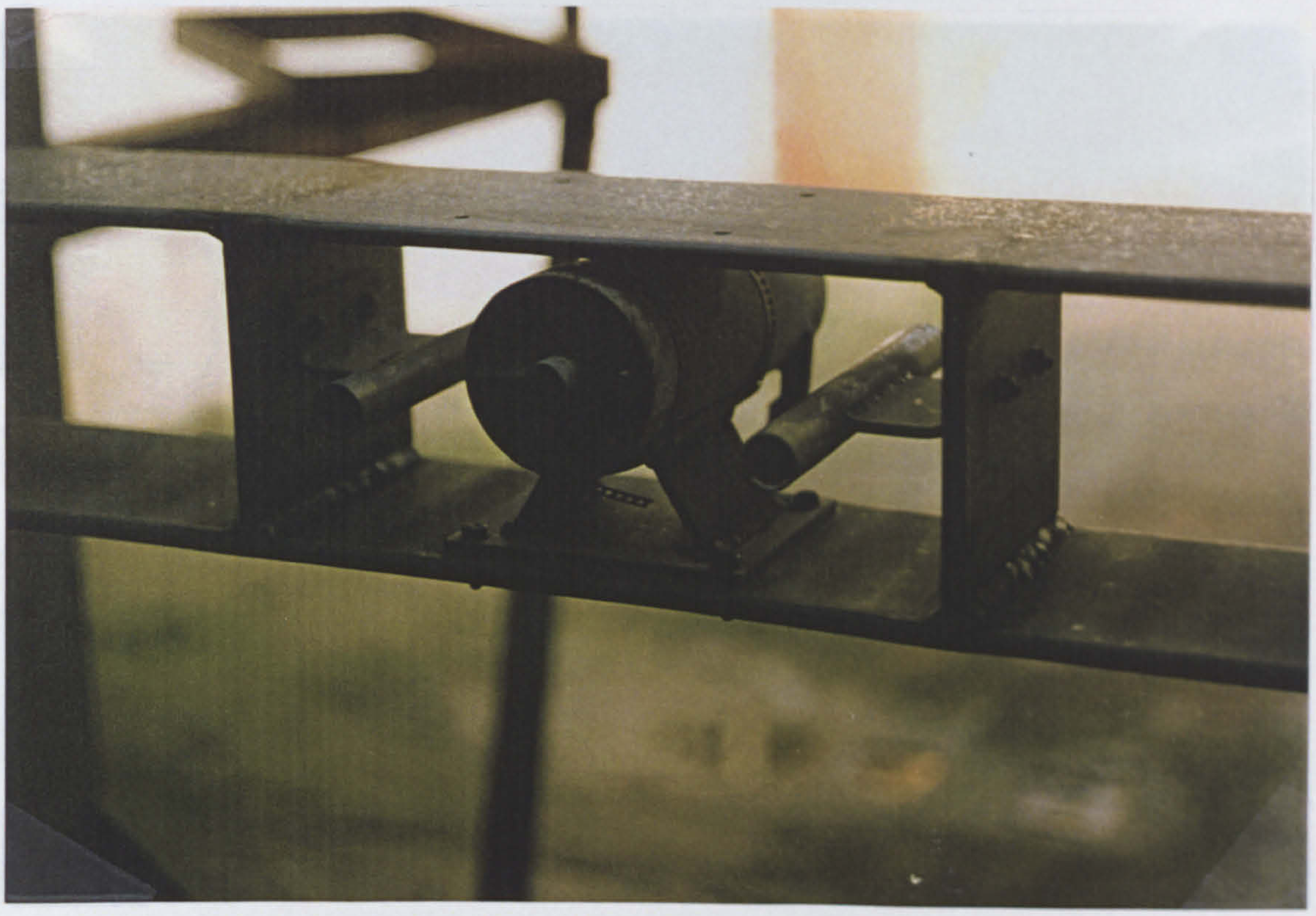


Figure 5.7 Centrisep post firing (proving trial)

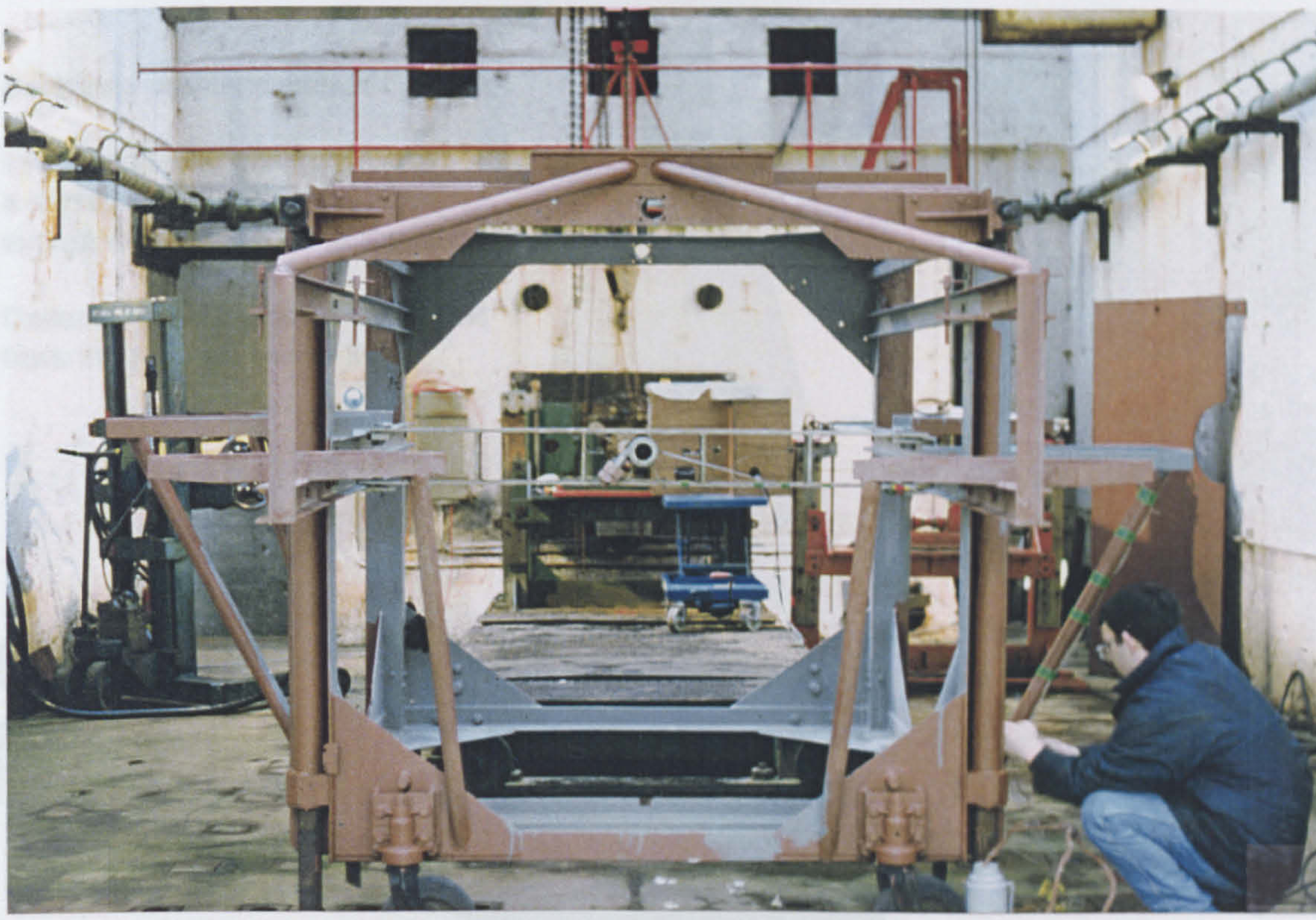


Figure 5.8 Centrisep supporting frame (proving trial)

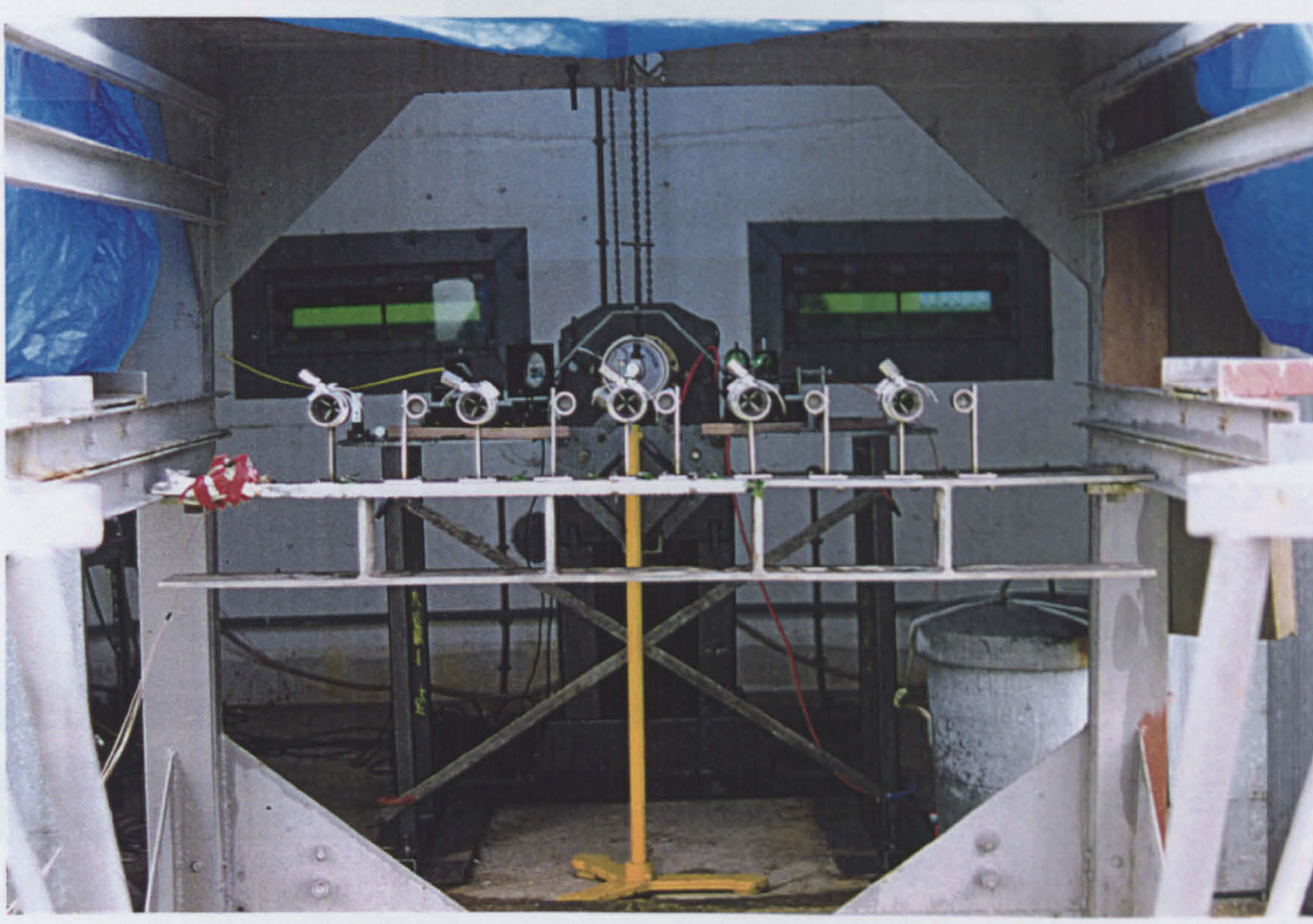


Figure 5.9 Centrisep supporting frame (Heavyweight motor trial)

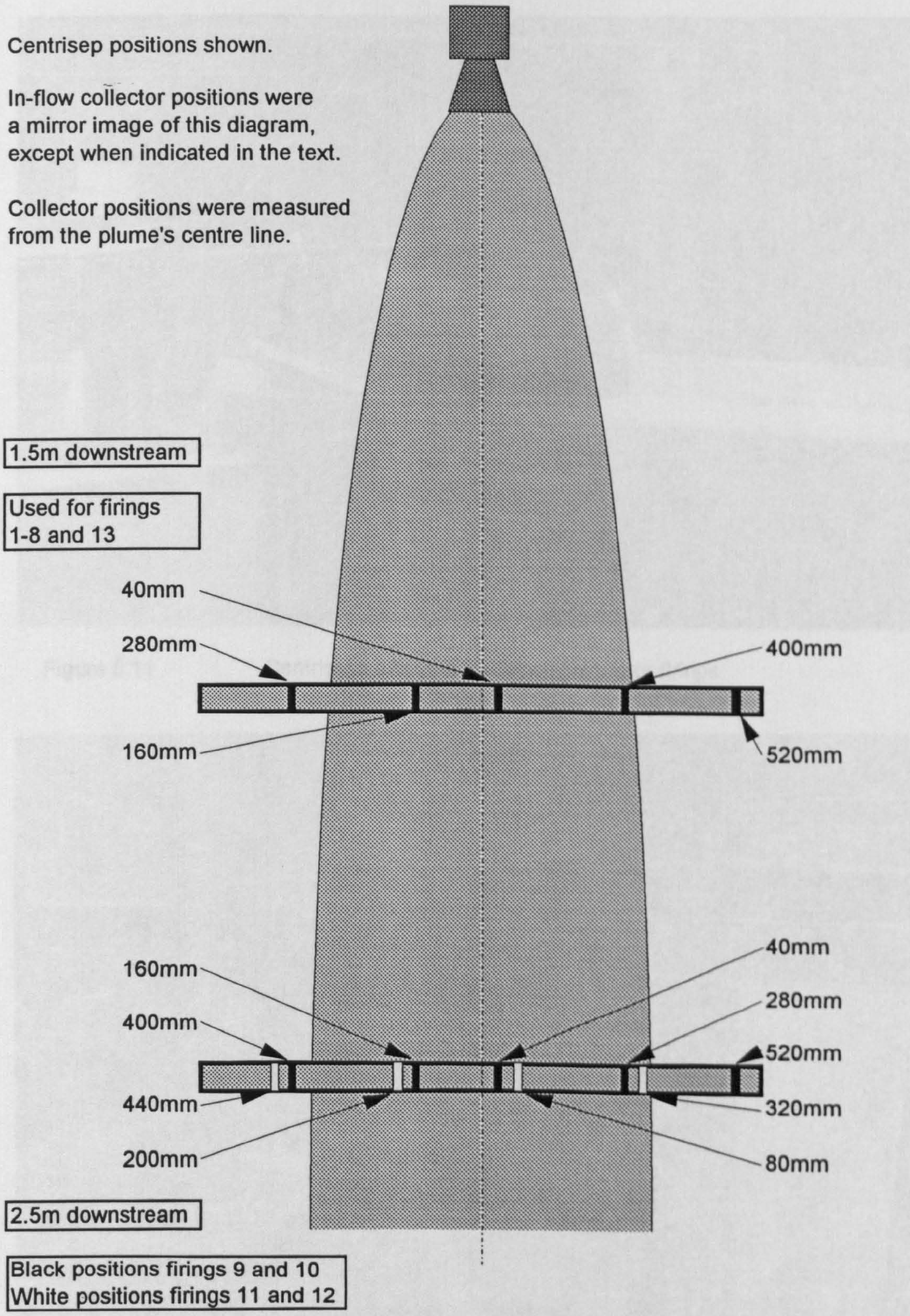


Figure 5.10 Schematic of particle collector positions (Heavyweight and CRV7 trials)

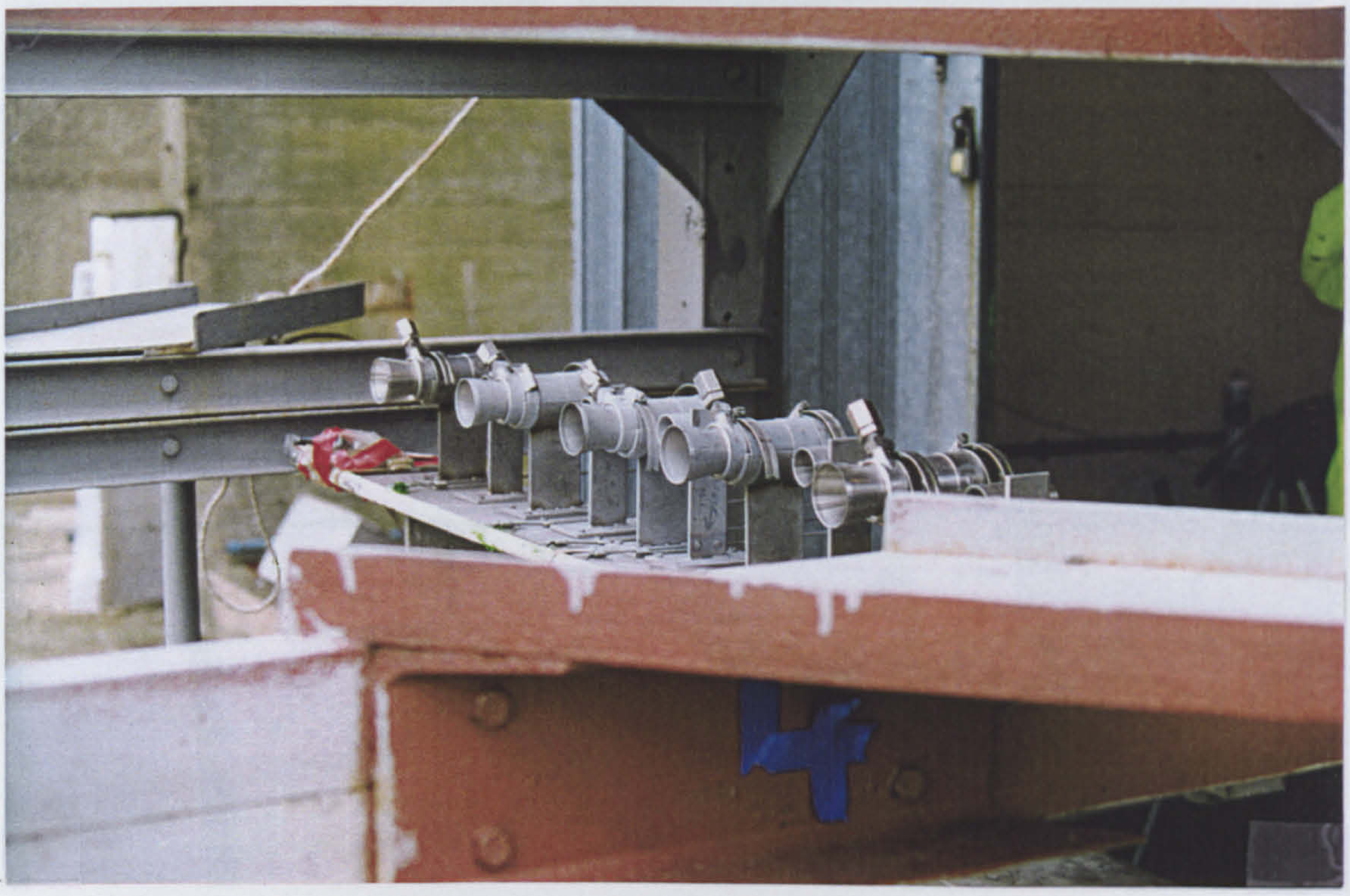


Figure 5.11 Centriseps after the Heavyweight motor firings

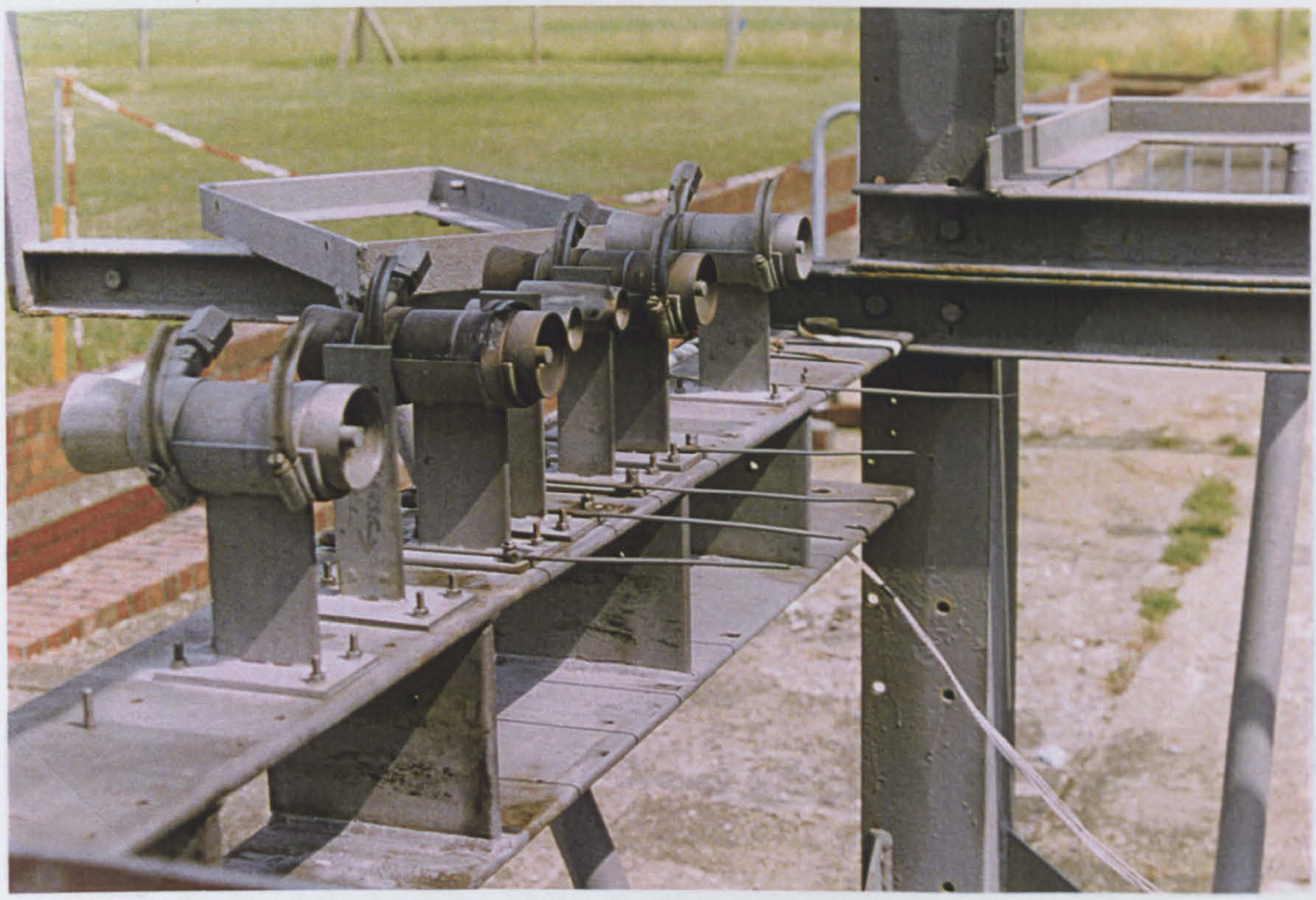


Figure 5.12 Centriseps after the CRV7 motor firings

Figure 5.13 Centriseps pictured during the firing of CRV7 motor (end on)

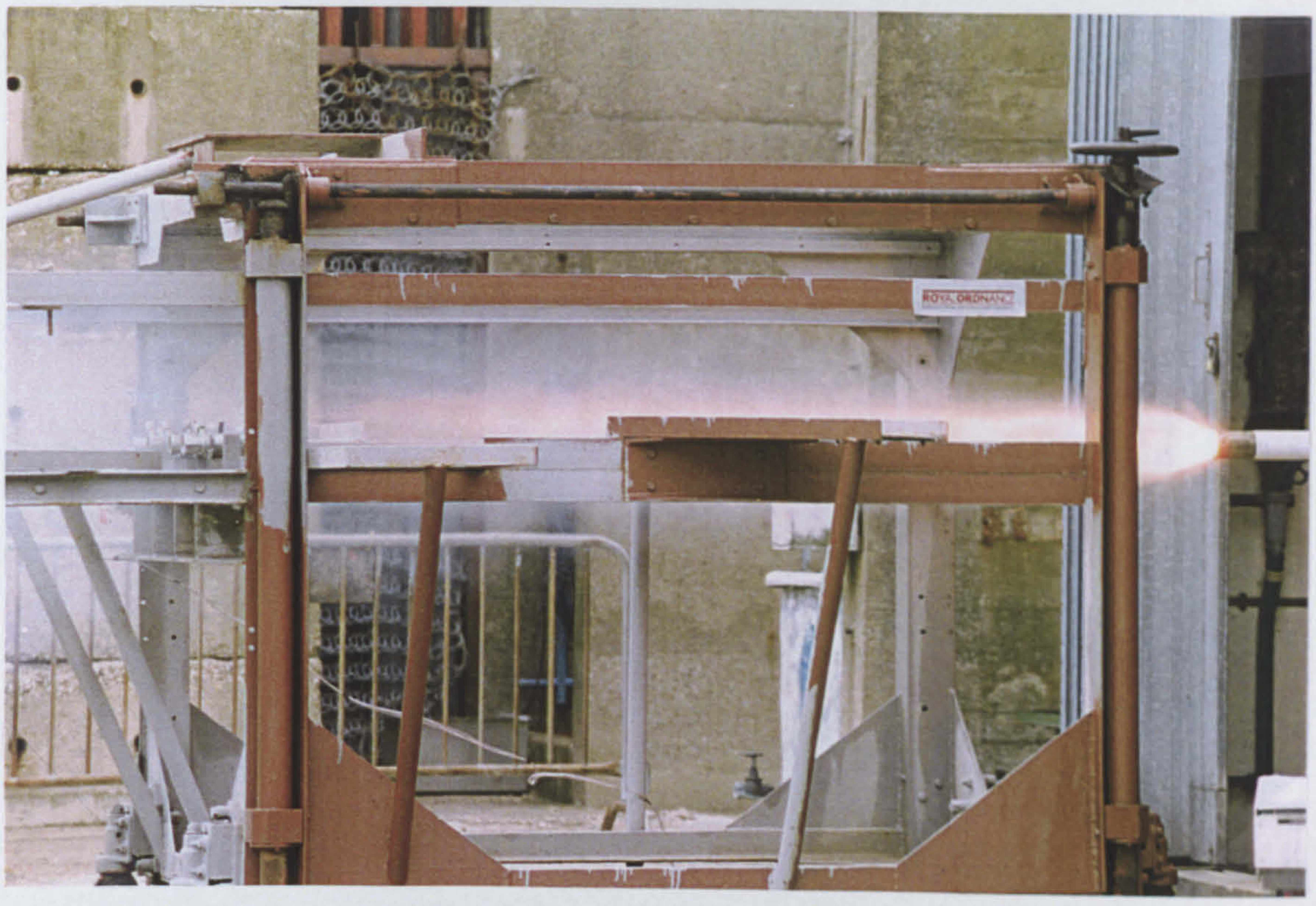


Figure 5.14 Centriseps pictured during the firing of CRV7 motor (side on)

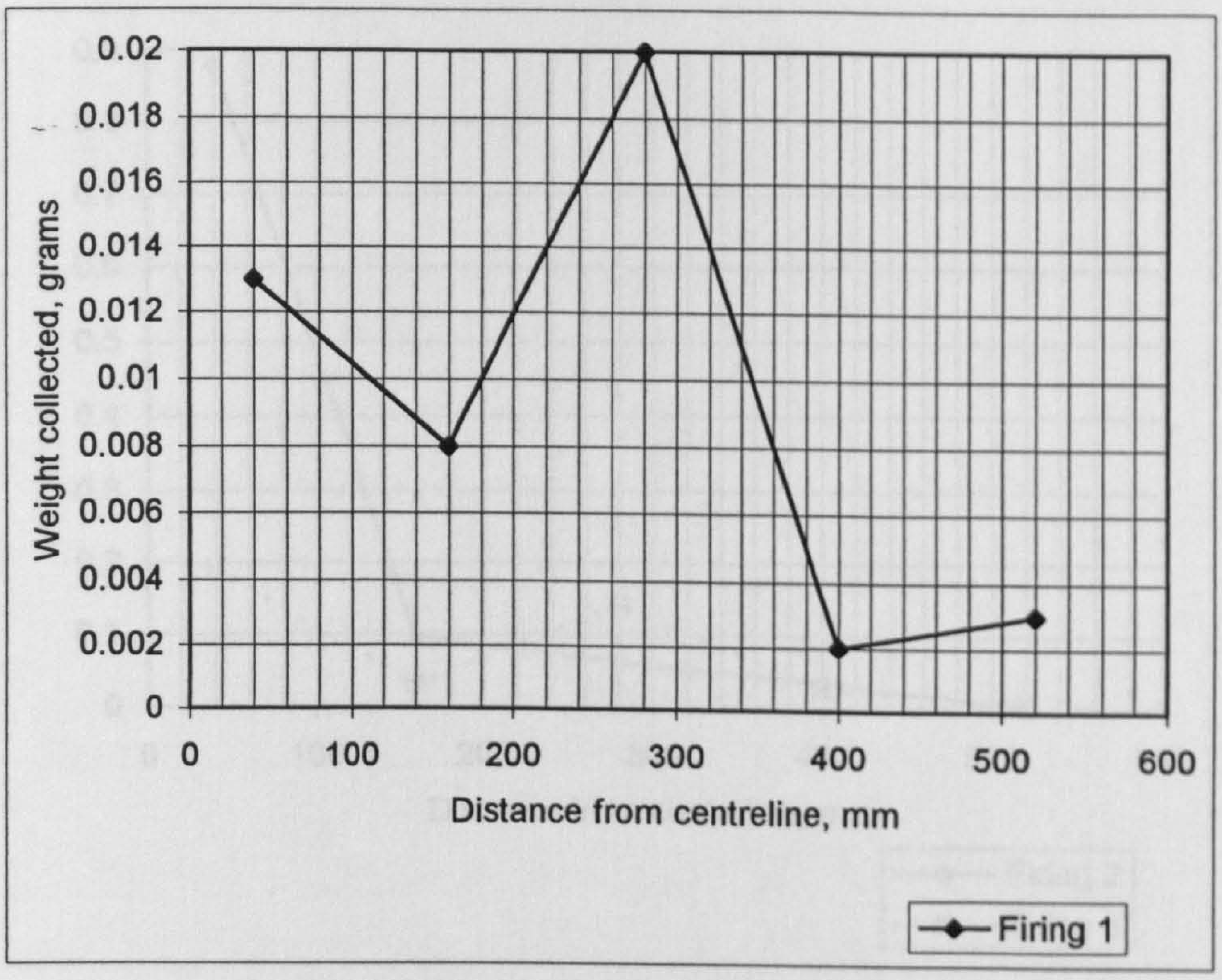


Figure 5.15 Weights of collected particles, CDB motor

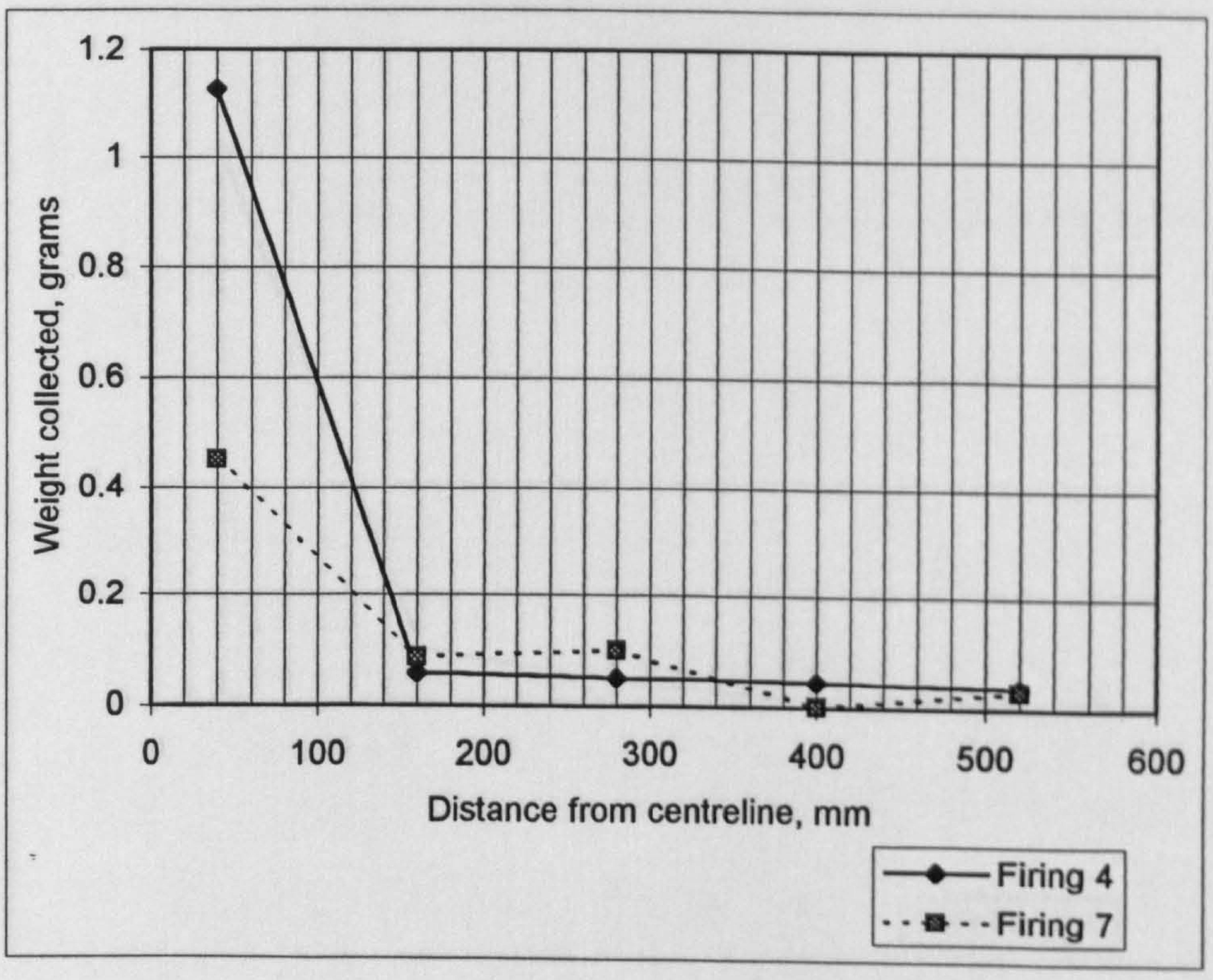


Figure 5.16 Weights of collected particles, 1% zirconia Heavyweight motor

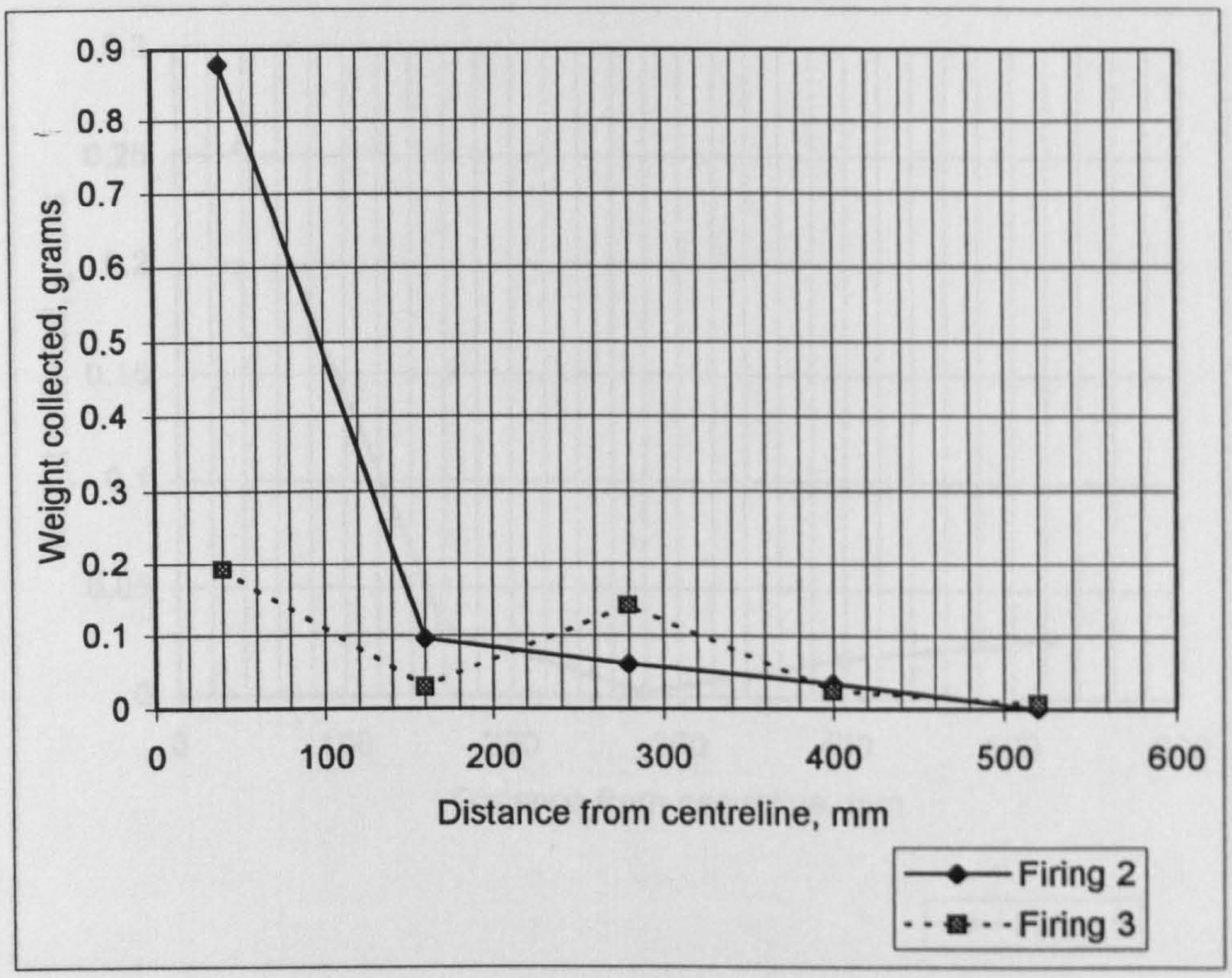


Figure 5.17 Weights of collected particle, 2% zirconia Heavyweight motor

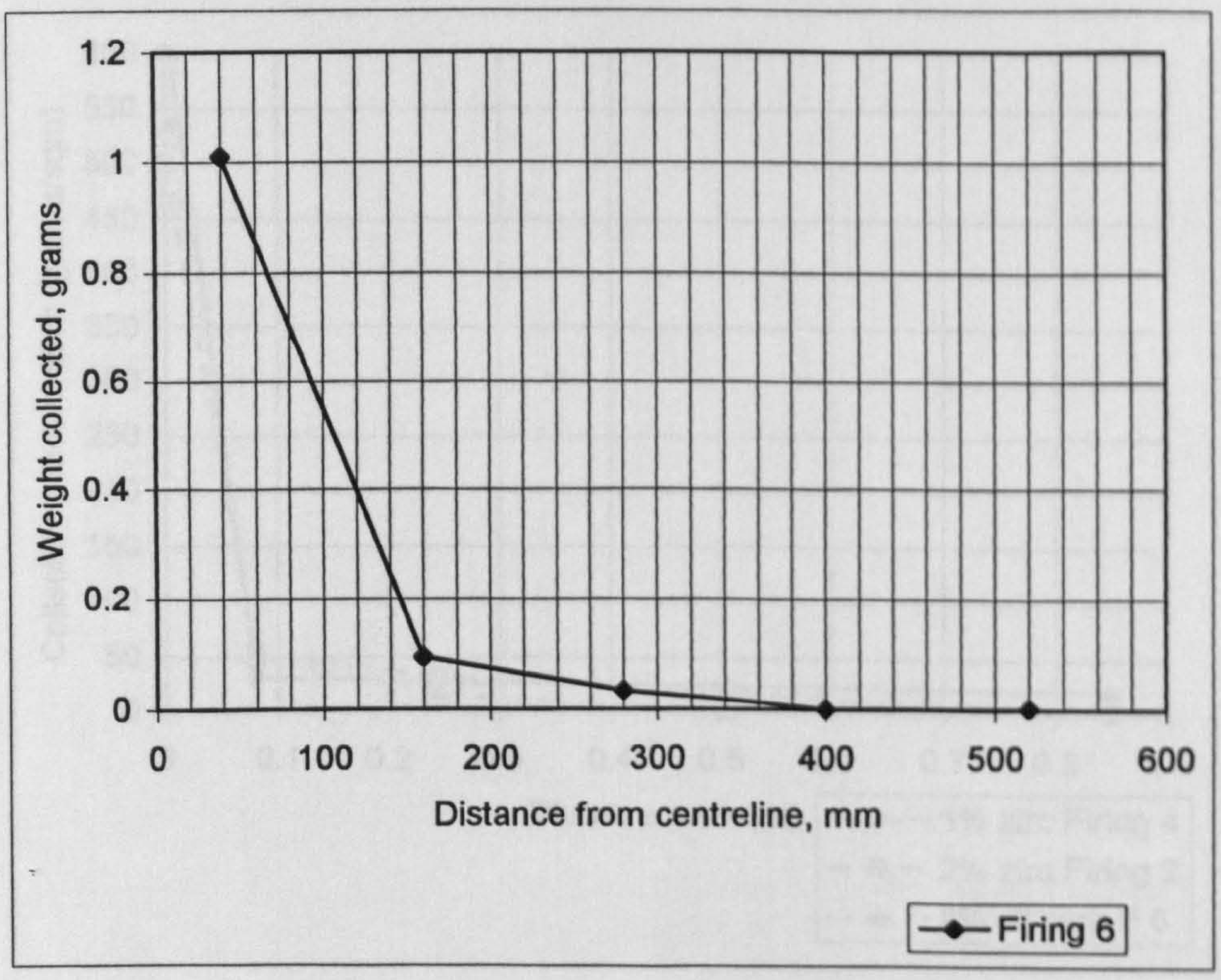


Figure 5.18 Weights of collected particles, 2% silicon carbide Heavyweight motor

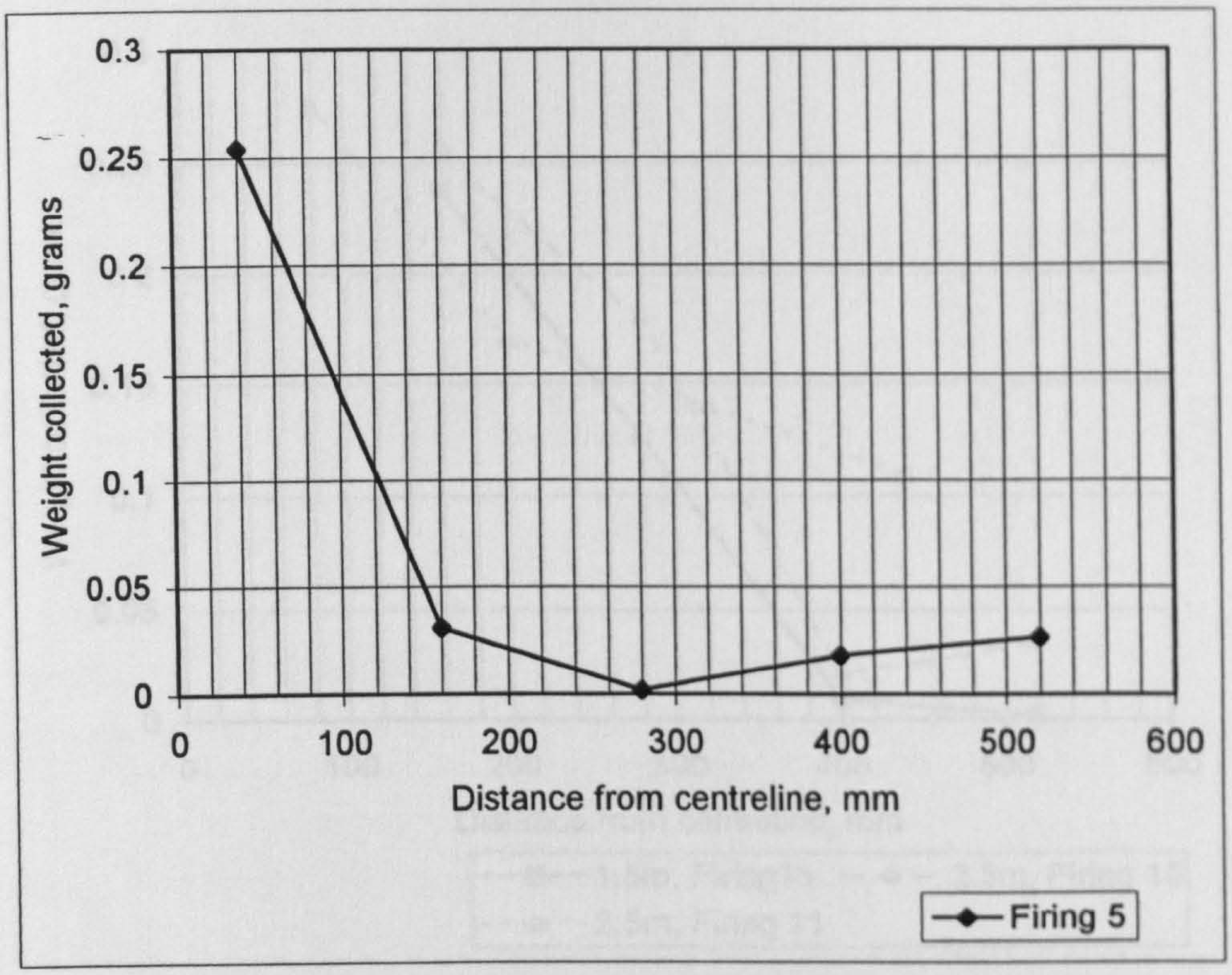


Figure 5.19 Weights of collected particles, unseeded Heavyweight motor

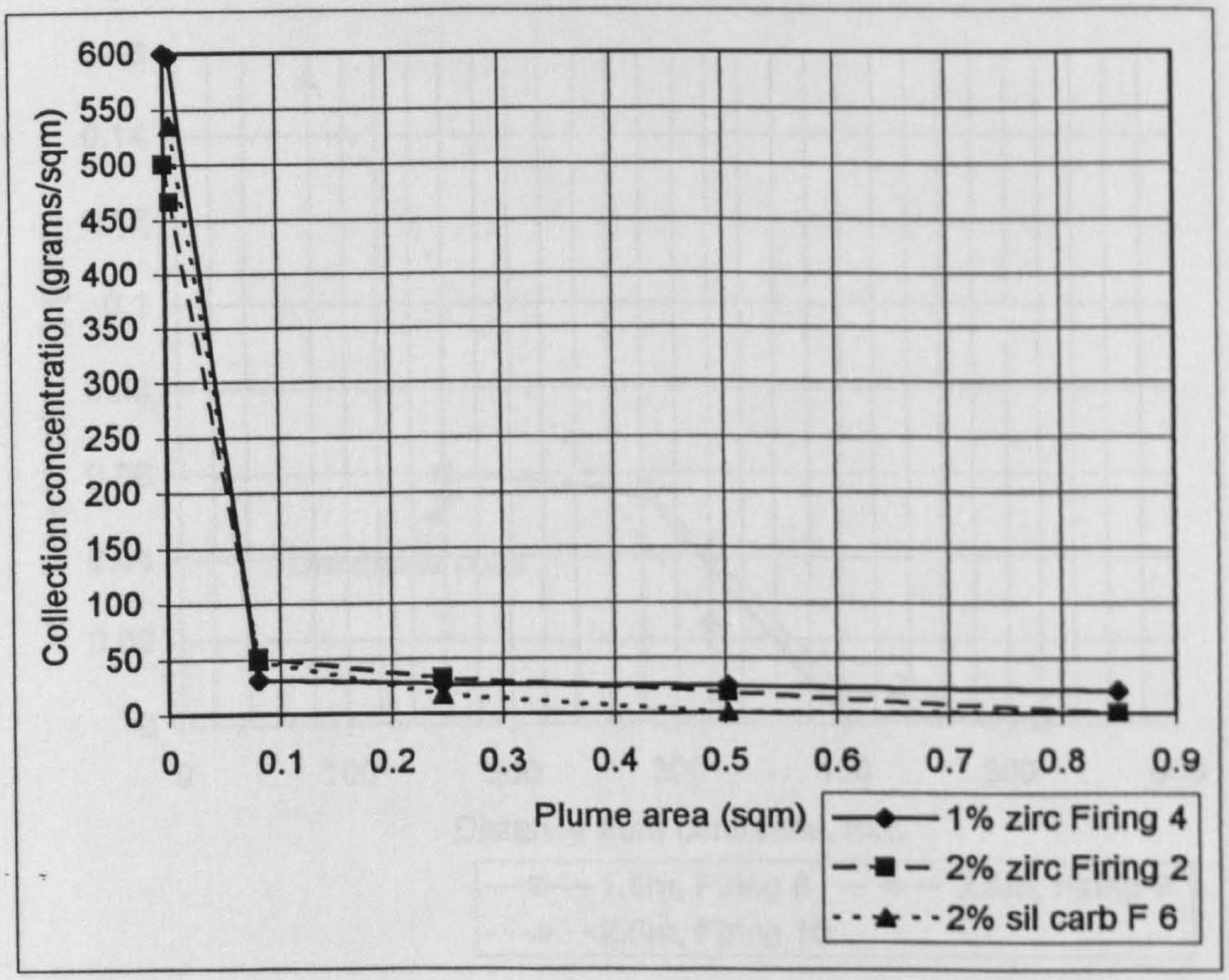


Figure 5.20 Particle collection concentations plotted against plume area

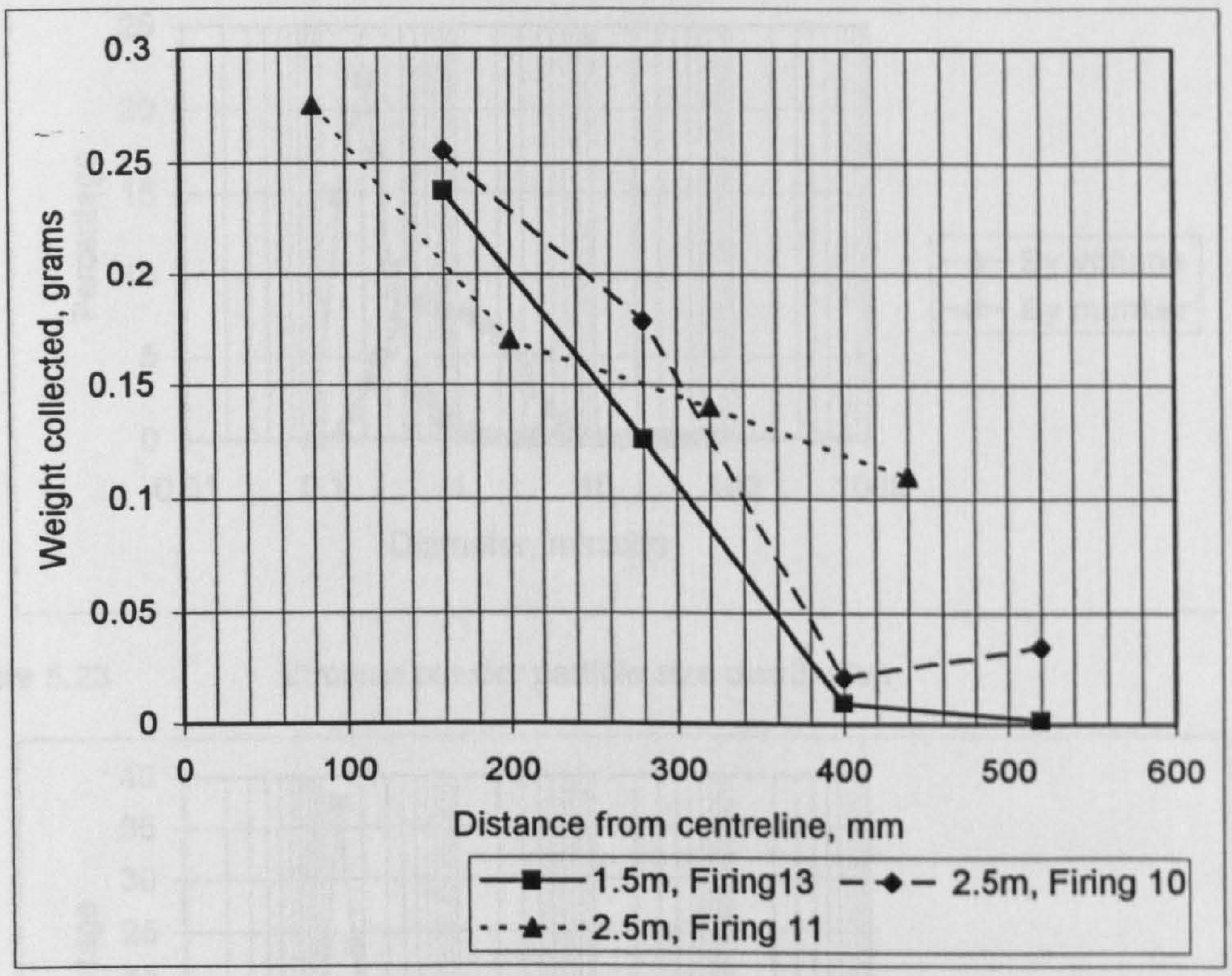


Figure 5.21 Weights of collected particles, CRV7 C14 motor

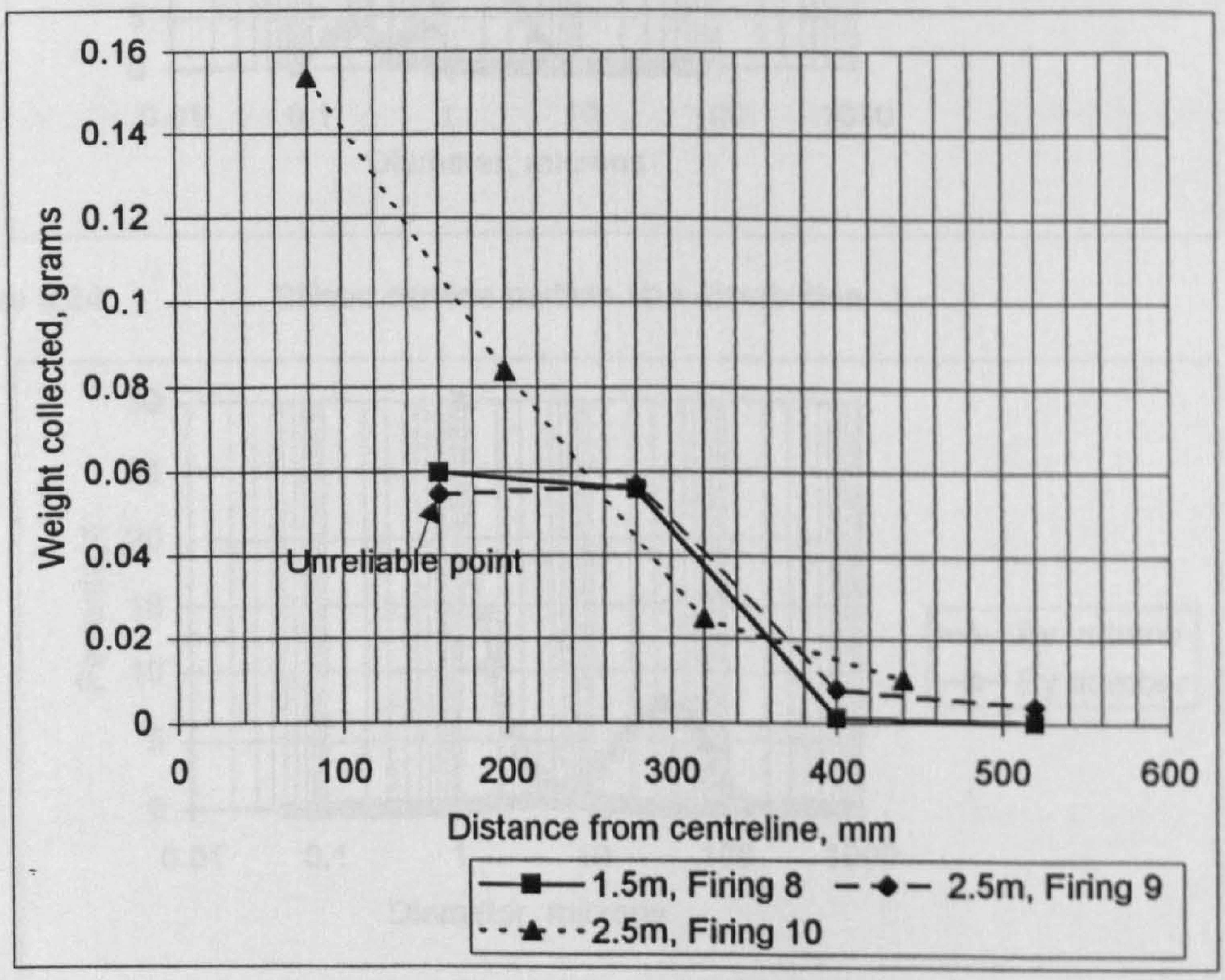


Figure 5.22 Weights of collected particles, CRV7 C15 motor

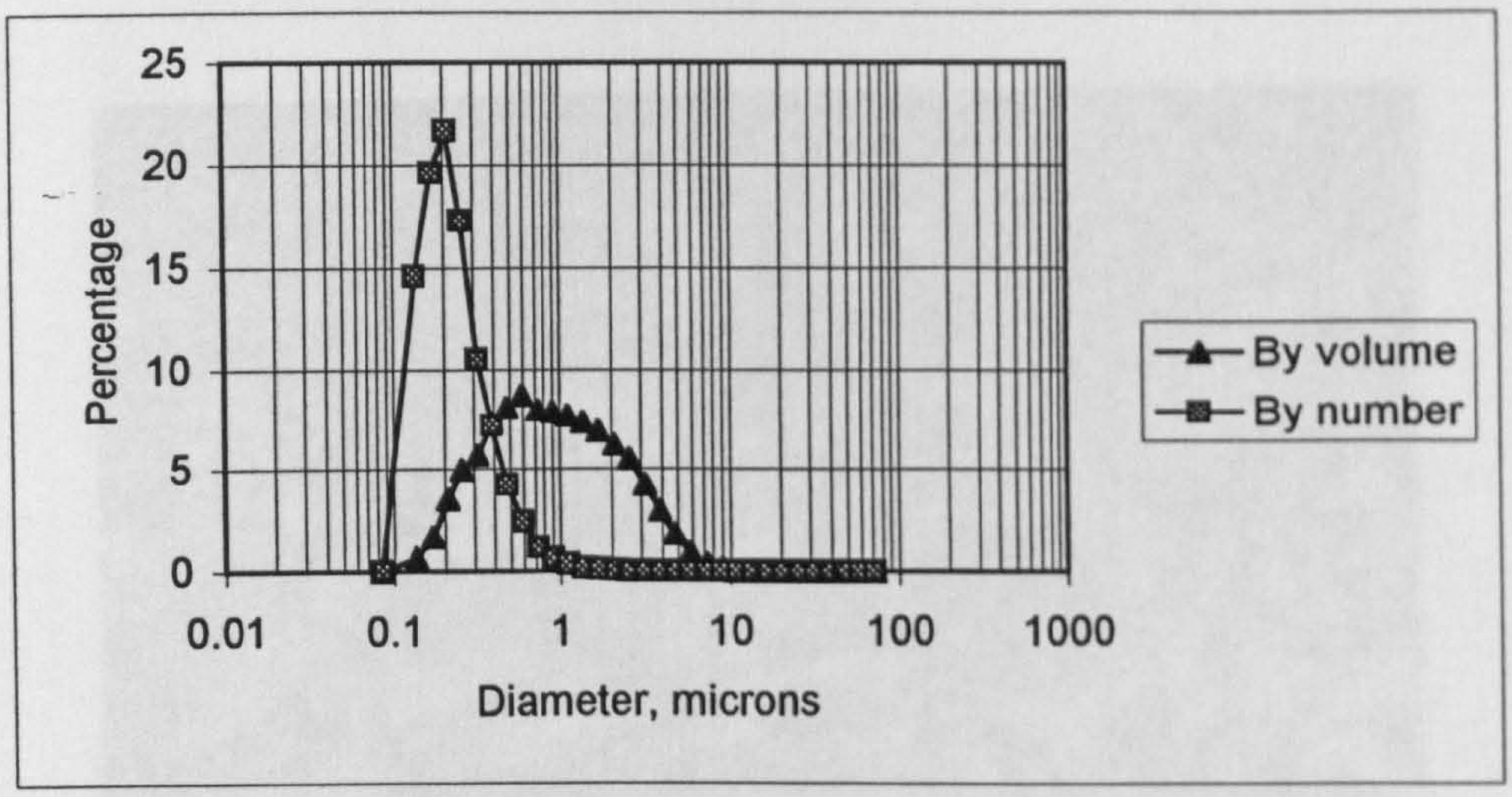


Figure 5.23 Zirconia powder particle size distribution

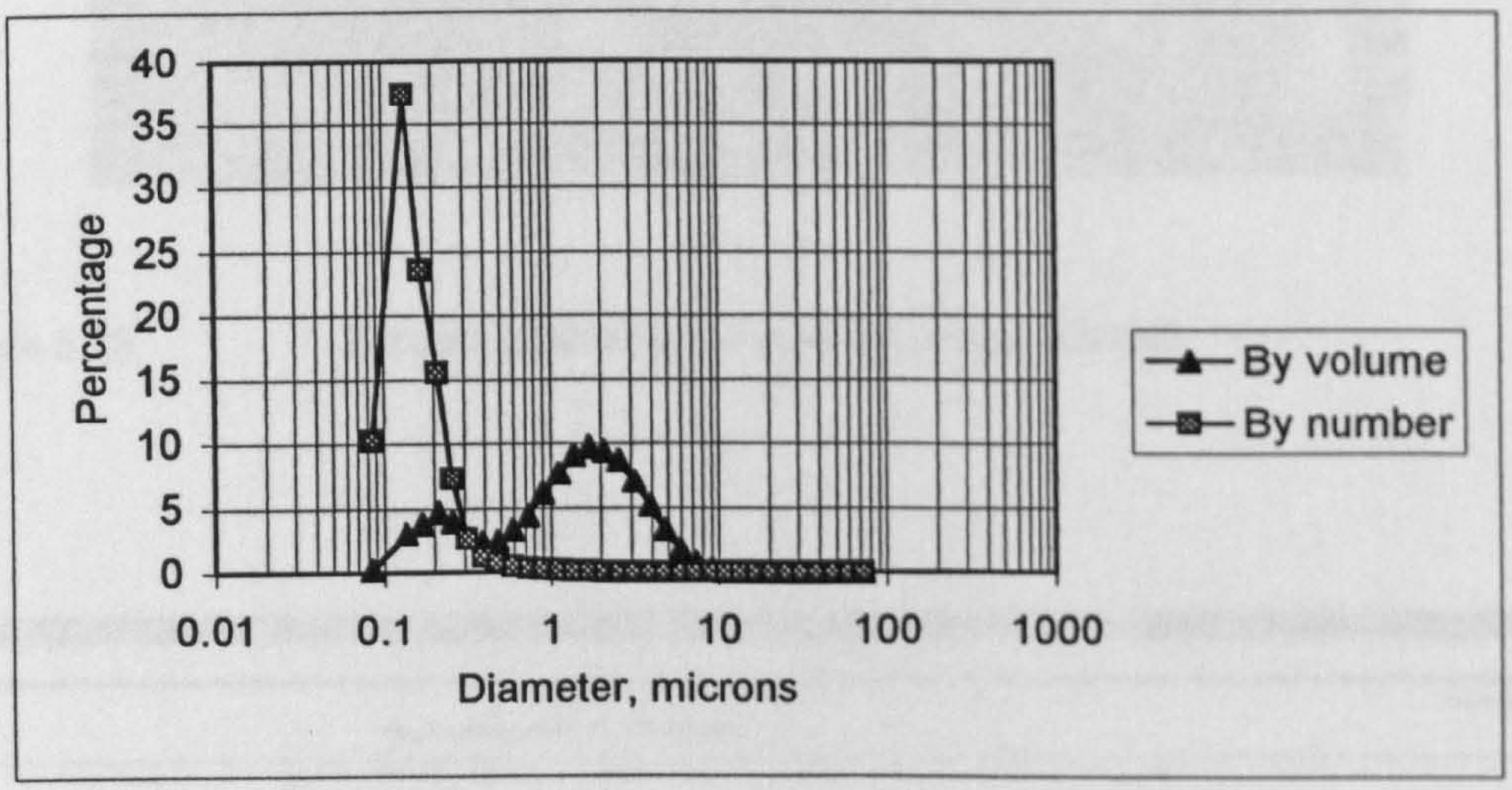


Figure 5.24 Silicon carbide particle size distribution

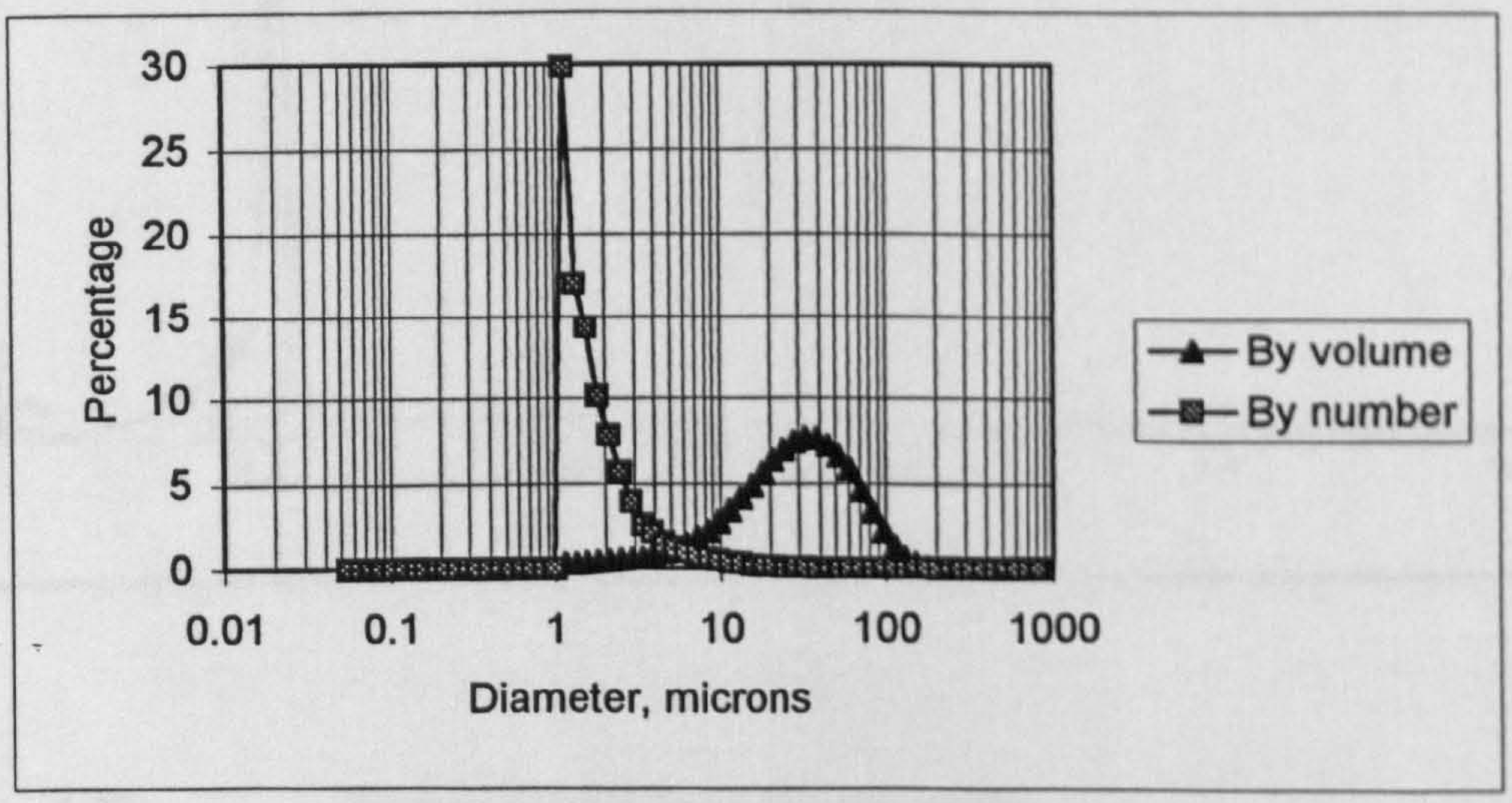


Figure 5.25 Aluminium powder particle size distribution

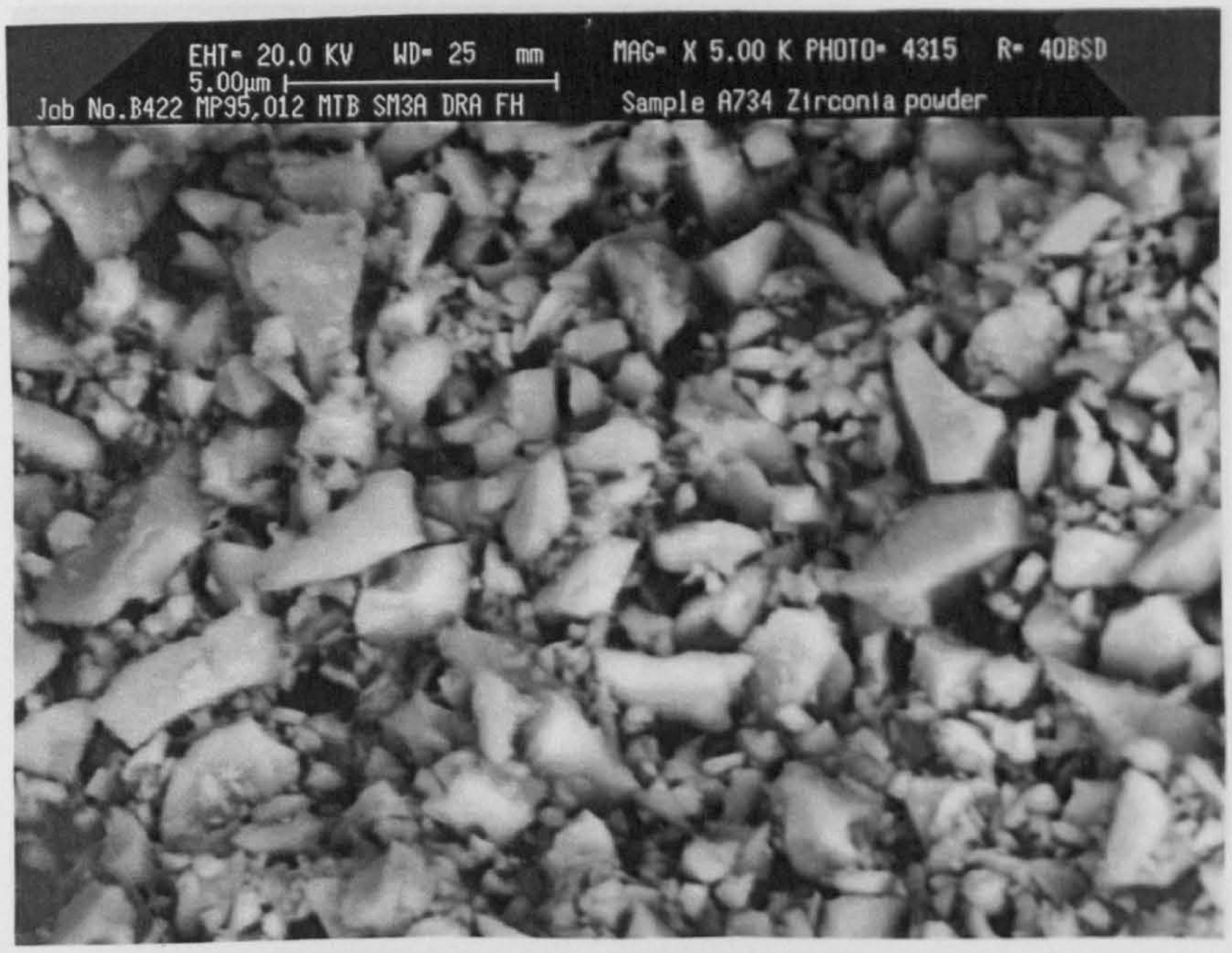


Figure 5.26 Zirconia powder SEM analysis image (X5000)

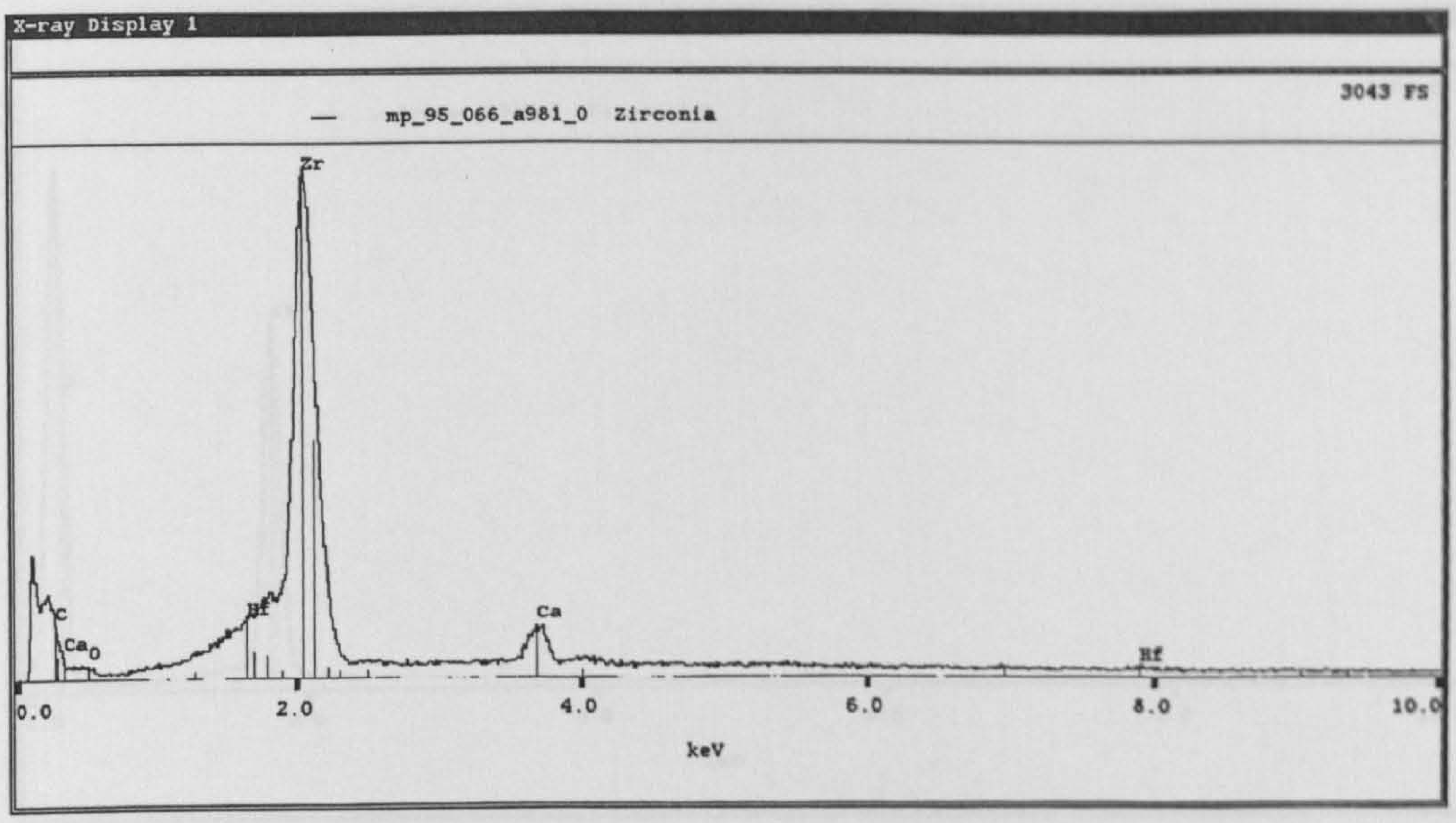


Figure 5.27 Zirconia powder SEM analysis graph

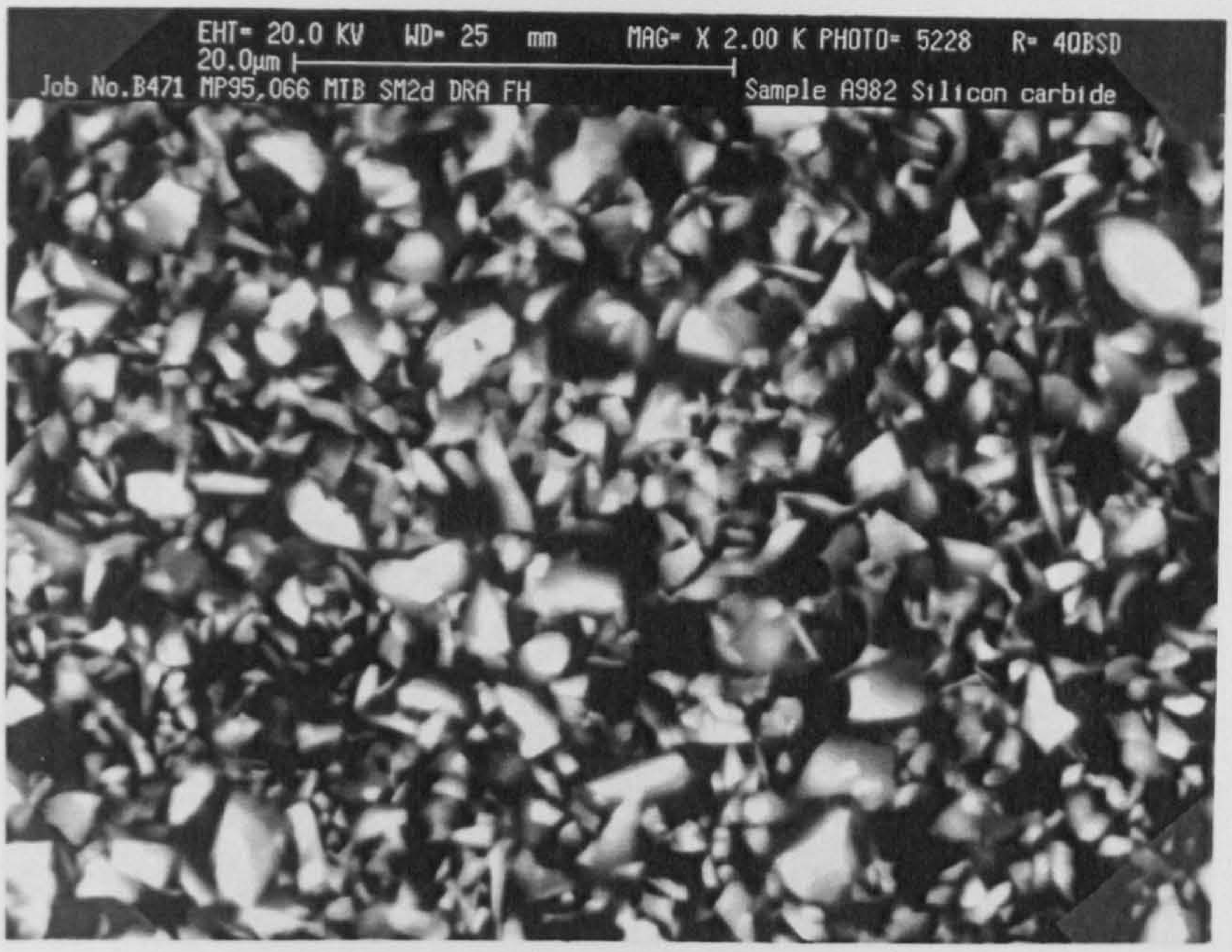


Figure 5.28 Silicon carbide powder SEM analysis image (x 2000)

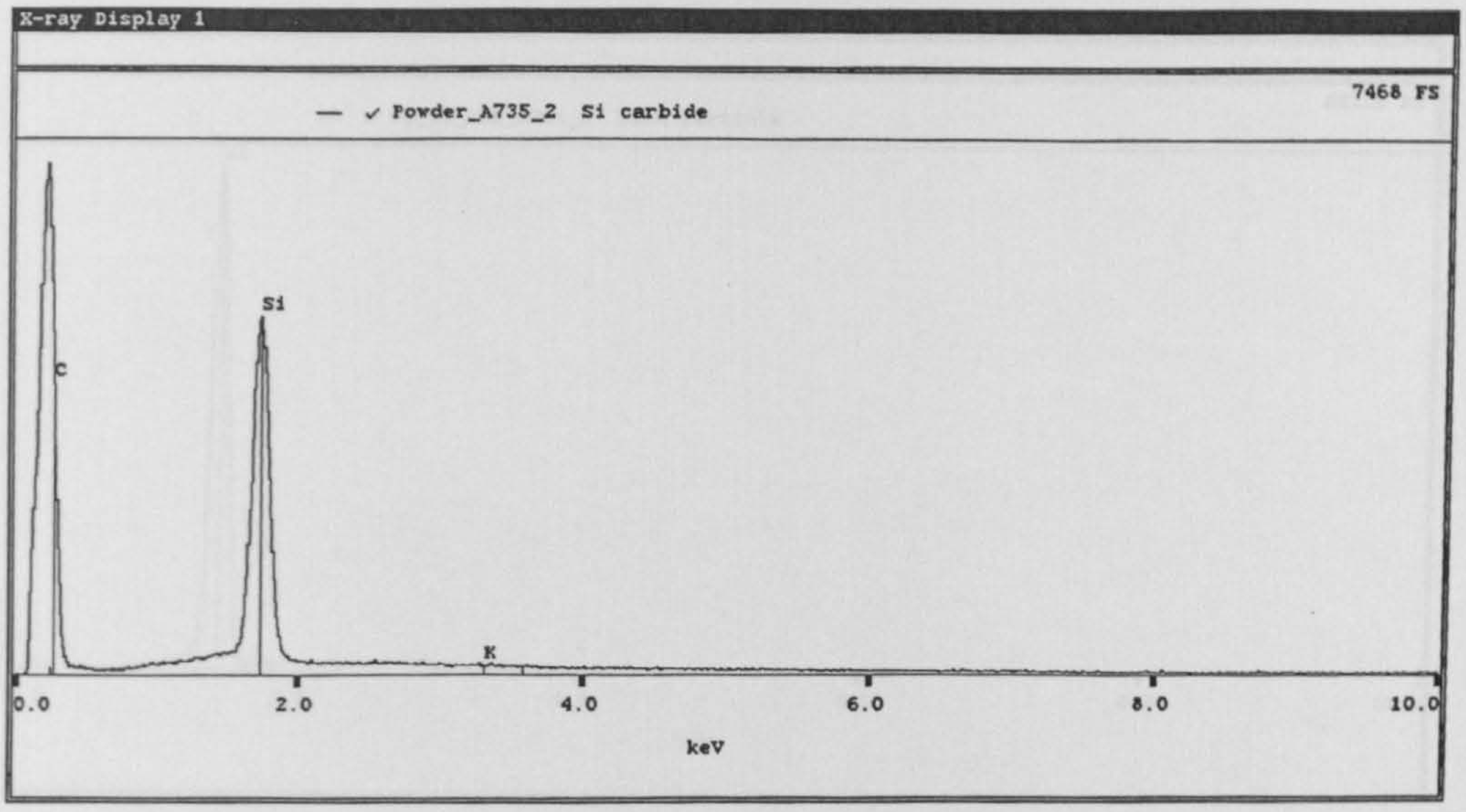


Figure 5.29 Silicon carbide powder SEM analysis graph

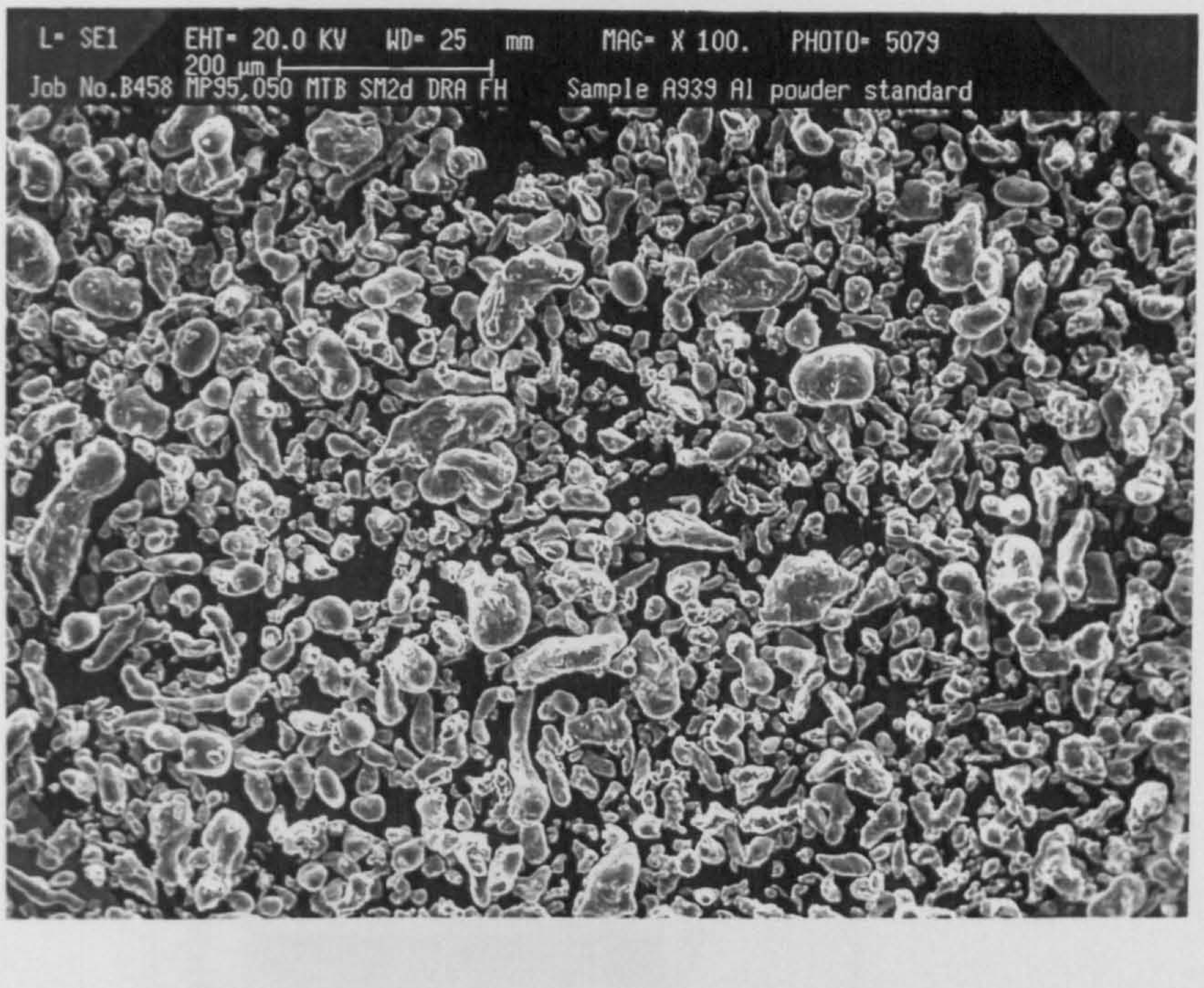


Figure 5.30 Aluminium powder SEM analysis image (x100)

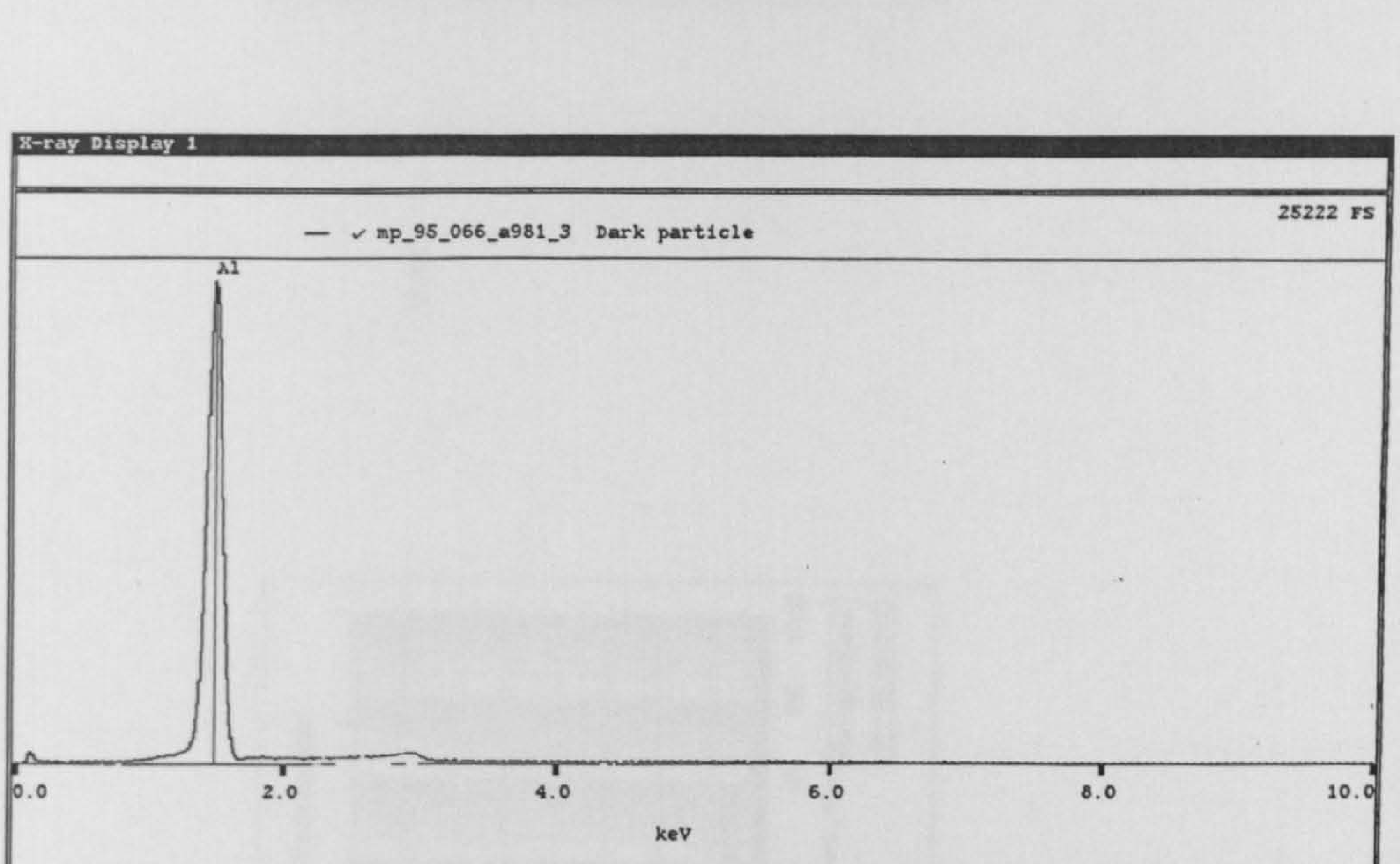
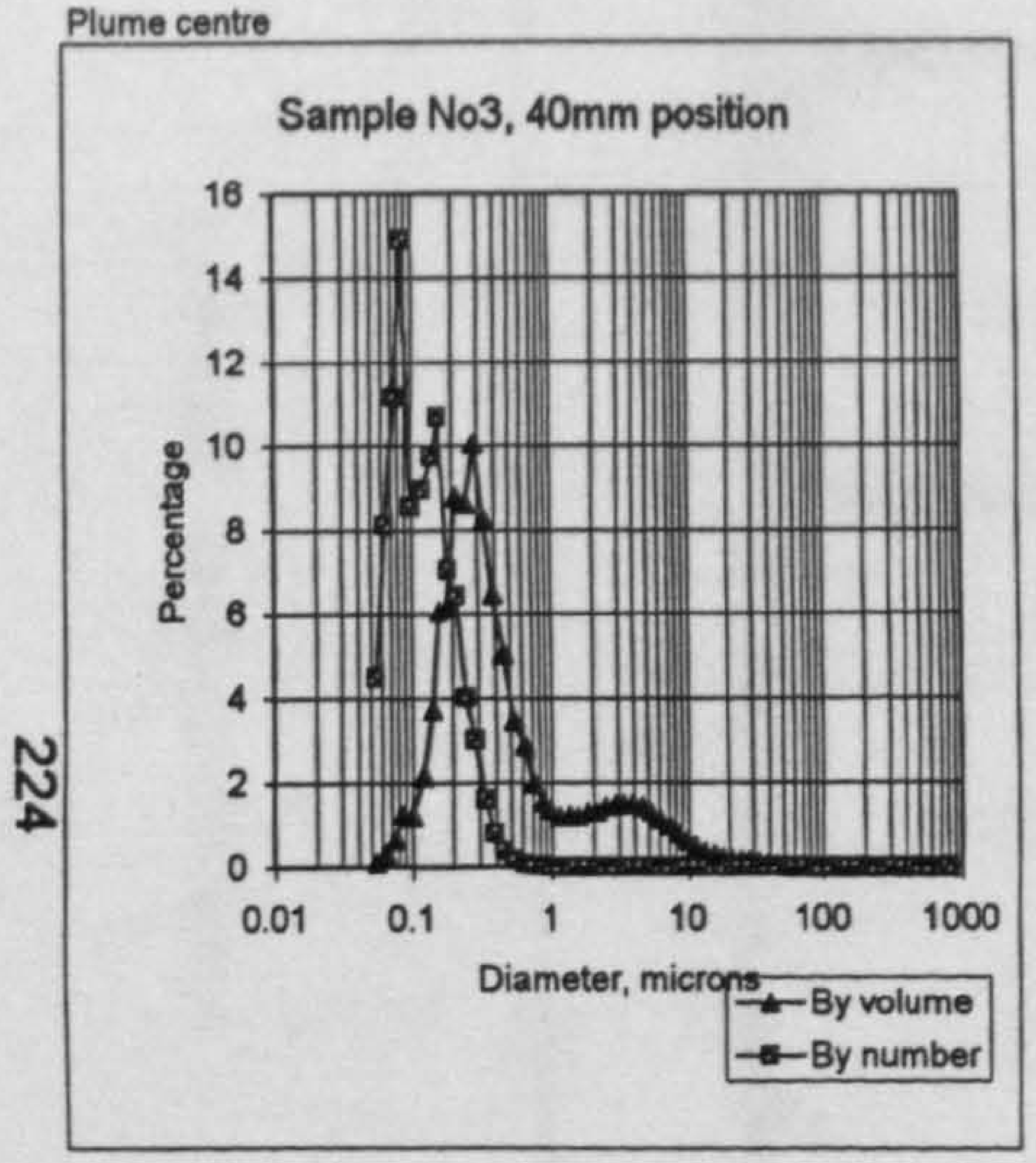
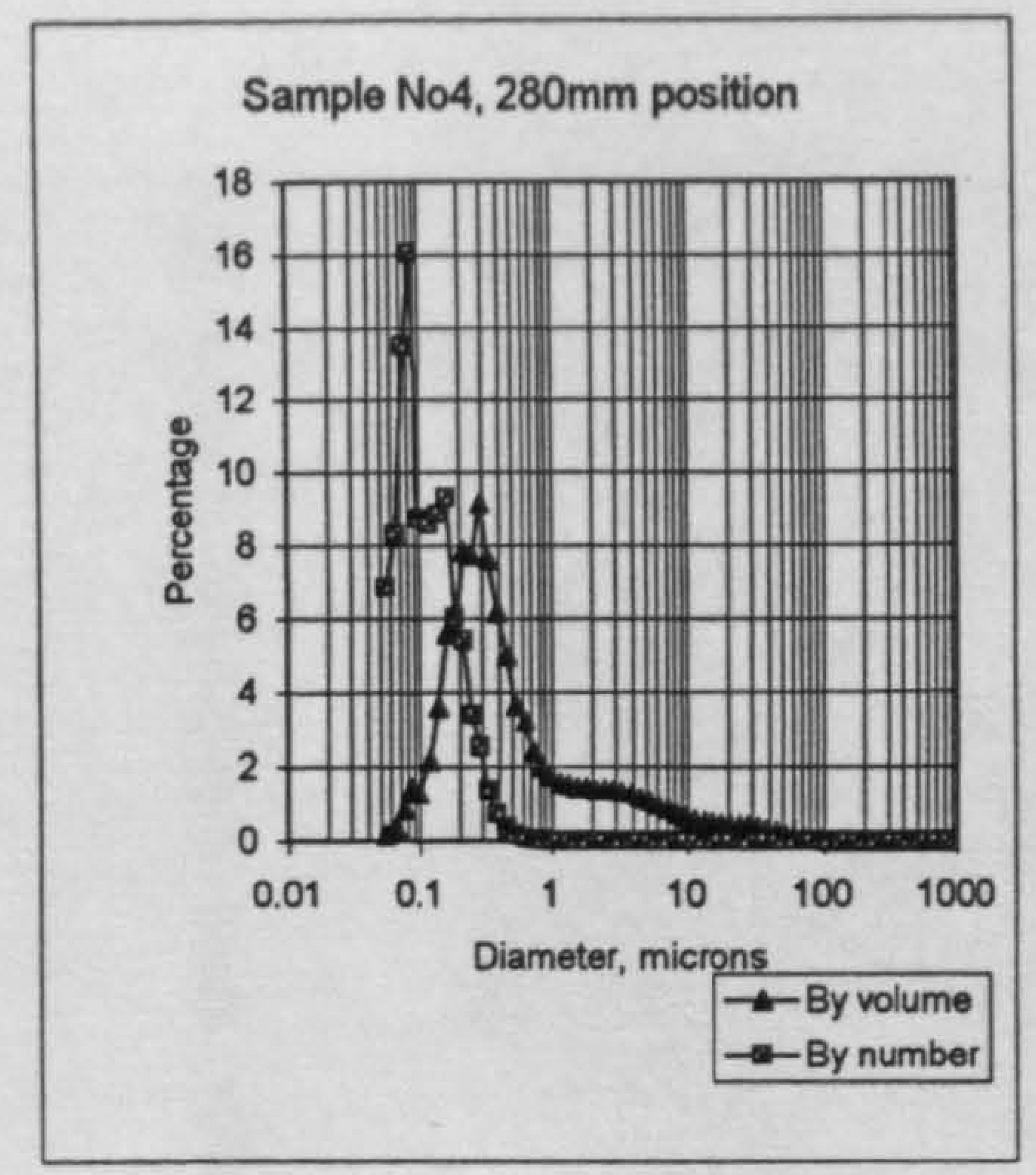


Figure 5.31 Aluminium powder SEM analysis graph

Plume centre



No data



No data

Figure 5.32 CDB motor particle size distribution (firing 1)

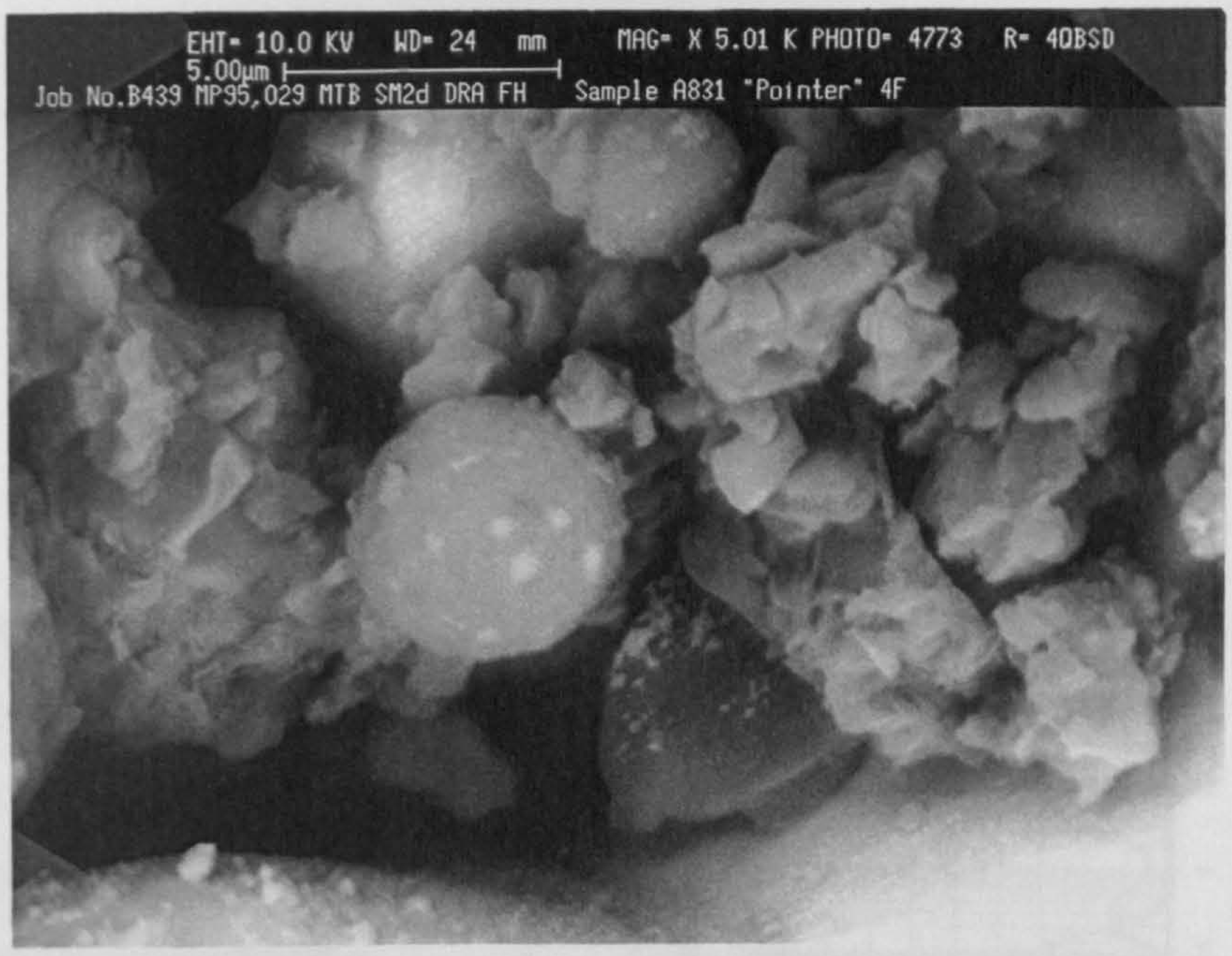


Figure 5.33 CDB motor SEM analysis image (x5010)

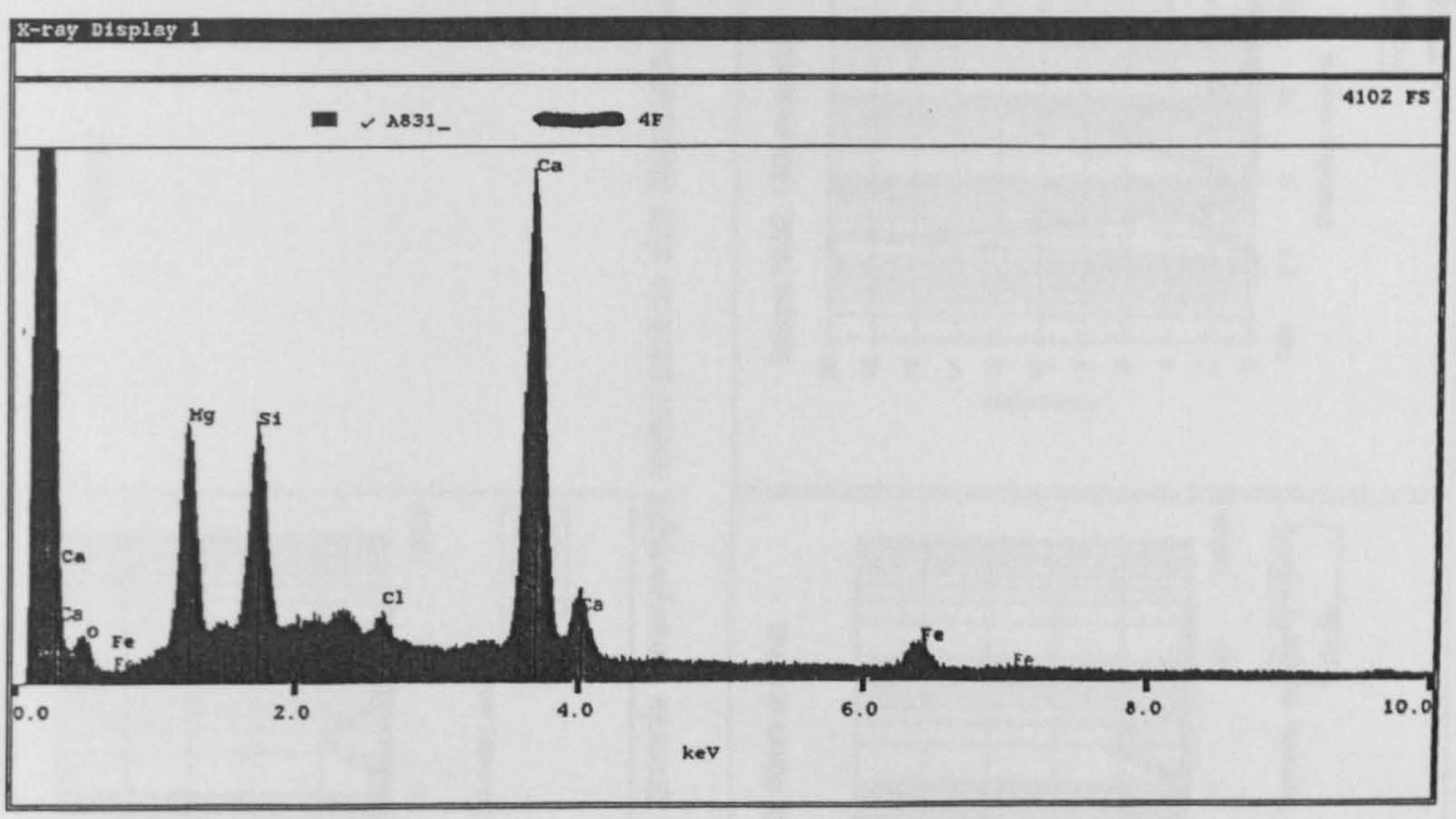


Figure 5.34 CDB motor SEM analysis graph

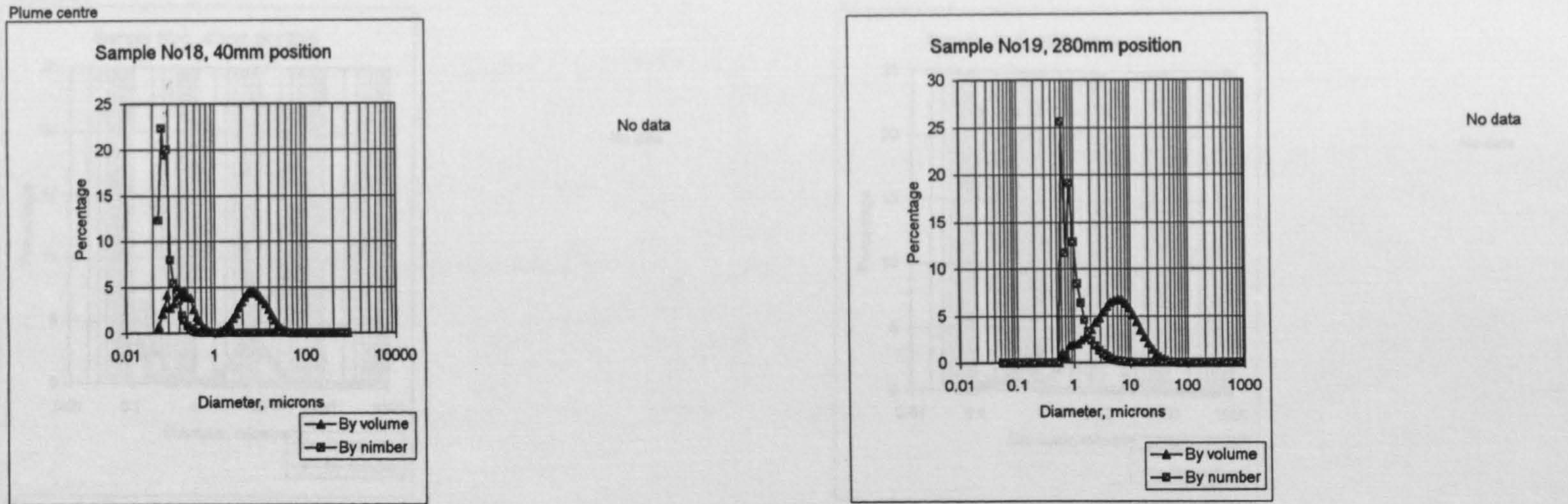


Figure 5.35 1% zirconia Heavyweight motor particle size distribution (firing 4)

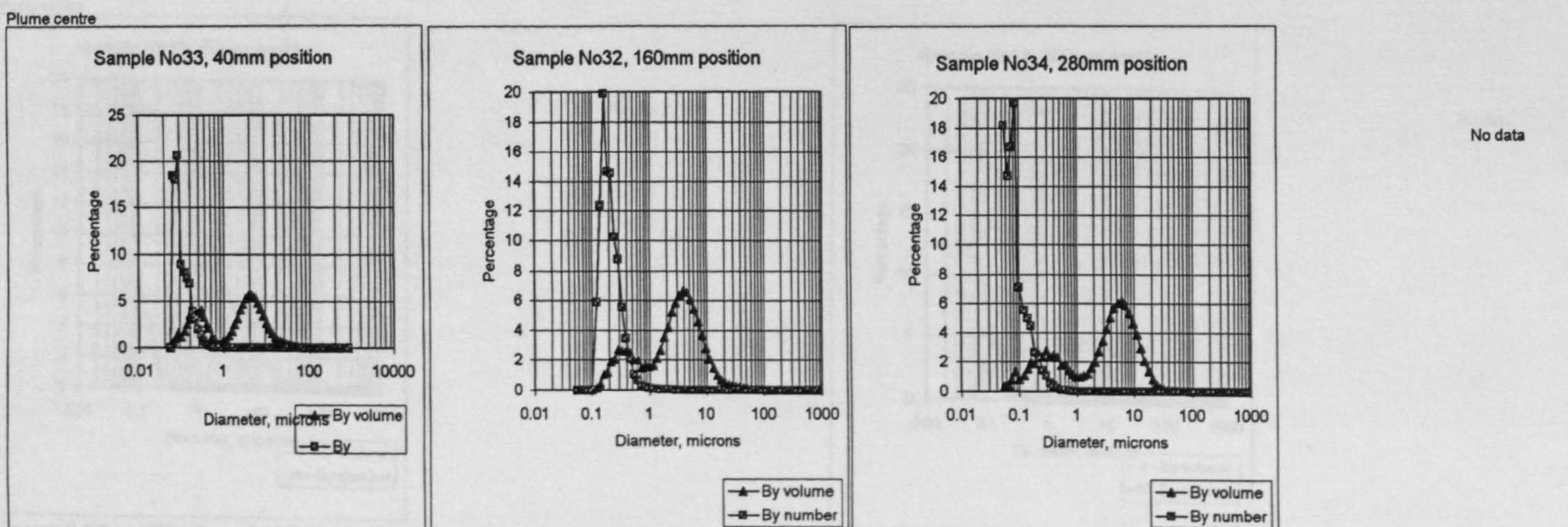


Figure 5.36 1% zirconia Heavyweight motor particle size distribution (firing 7)

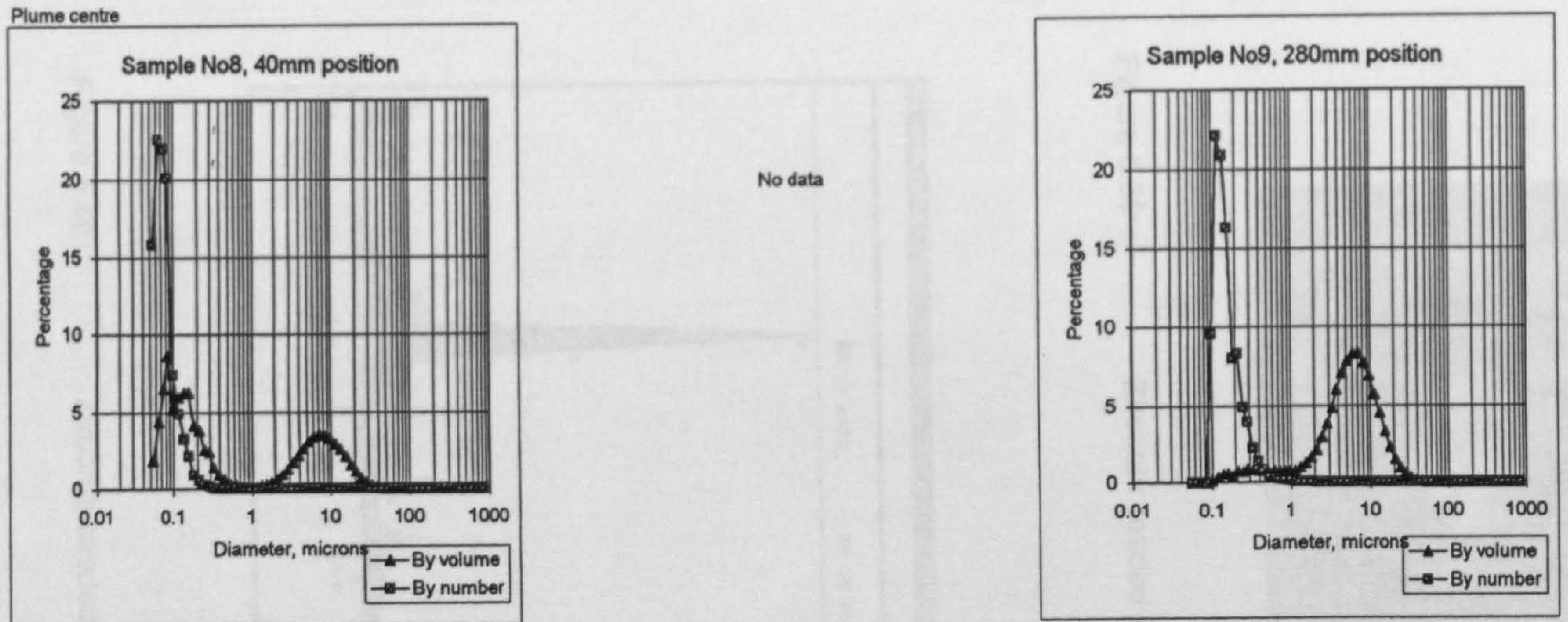


Figure 5.37 2% zirconia Heavyweight motor particle size distribution (firing 2)

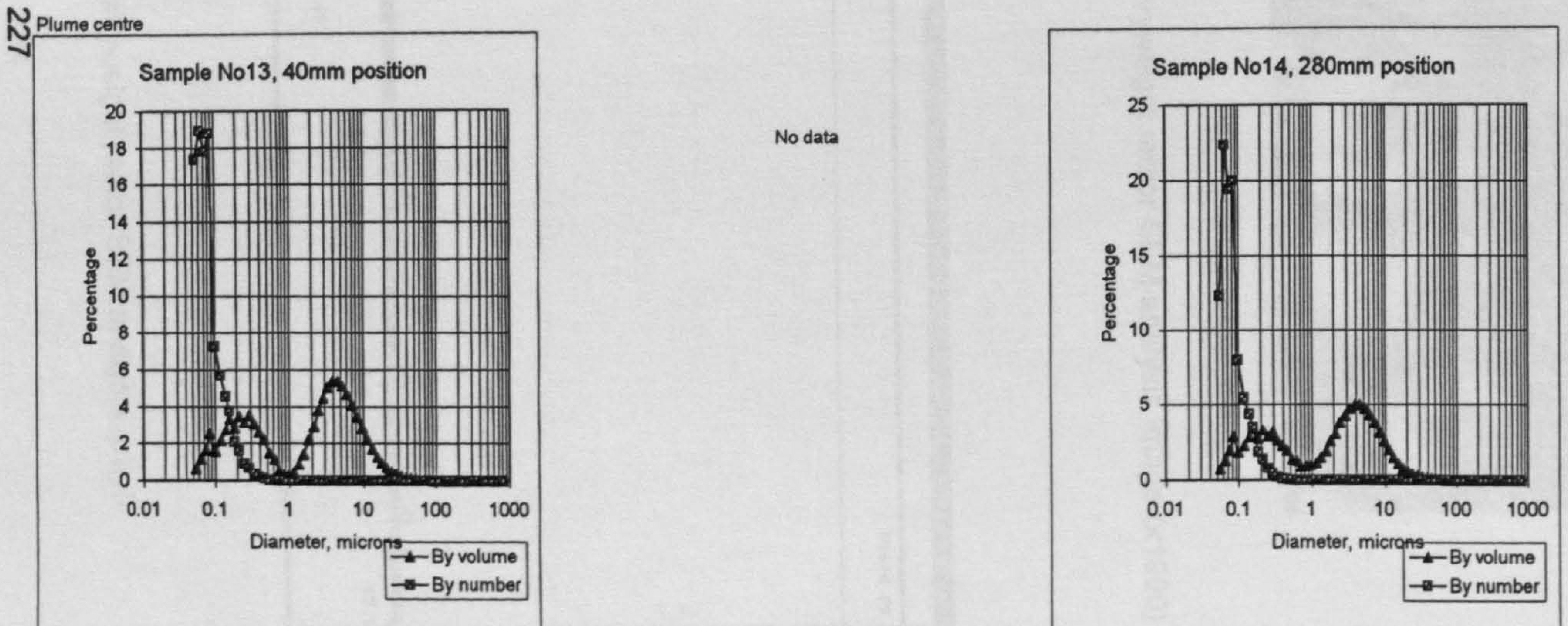


Figure 5.38 2% zirconia Heavyweight motor particle size distribution (firing 3)

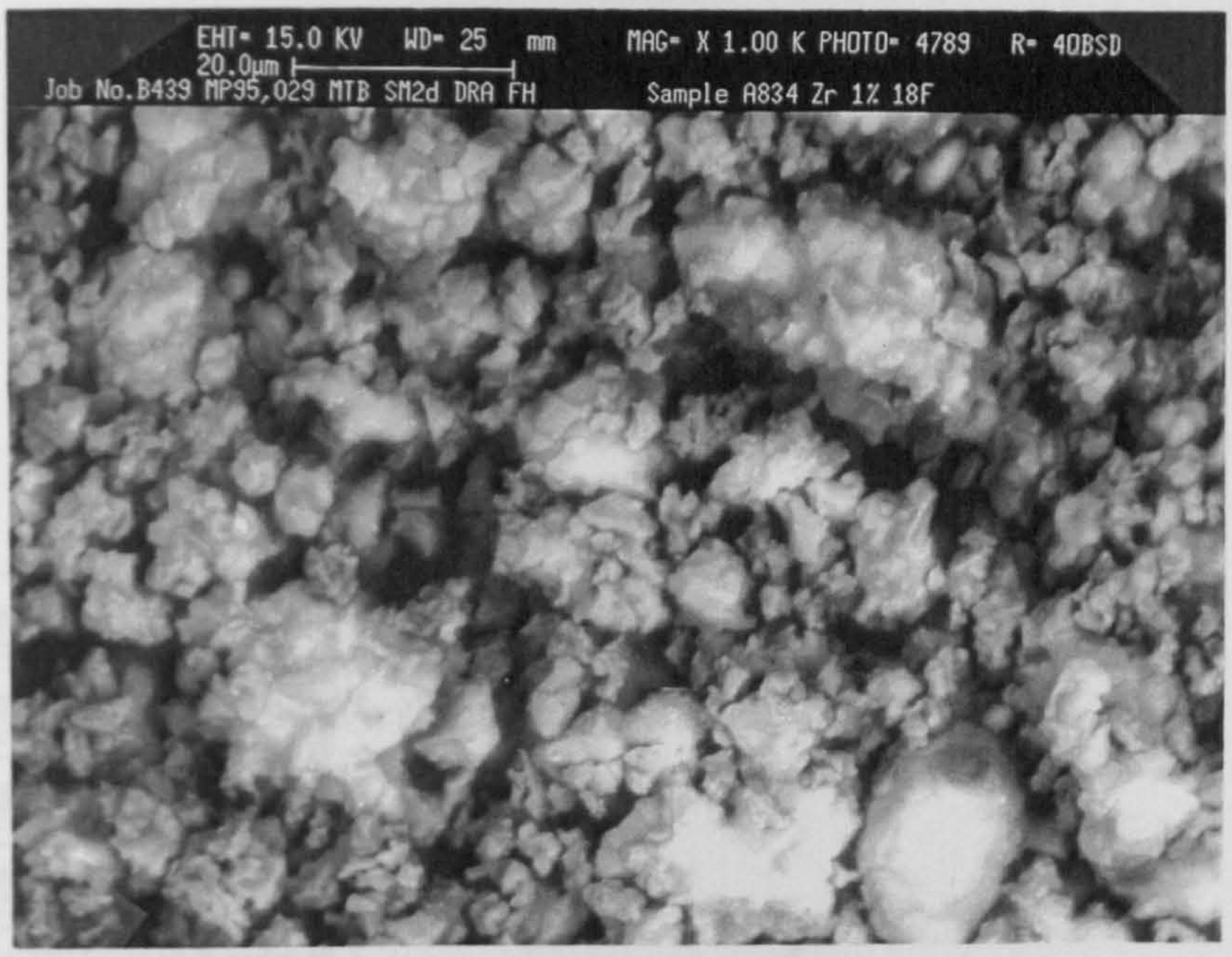


Figure 5.39 Zirconia seeded Heavyweight motor SEM analysis image (x1000)

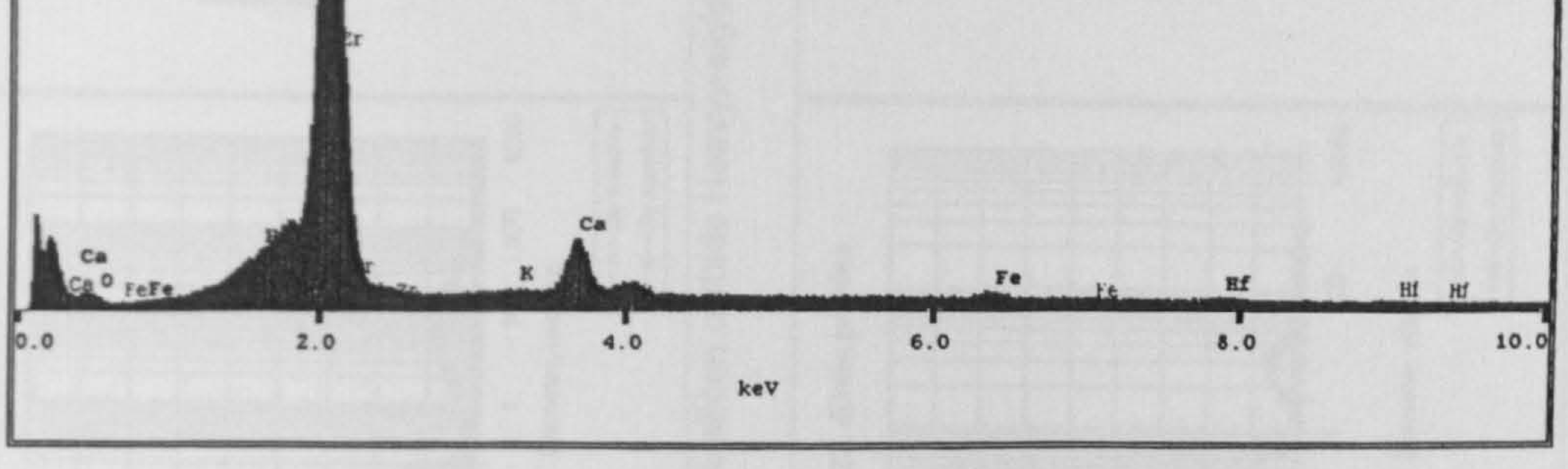


Figure 5.40 Zirconia seeded Heavyweight motor SEM analysis graph

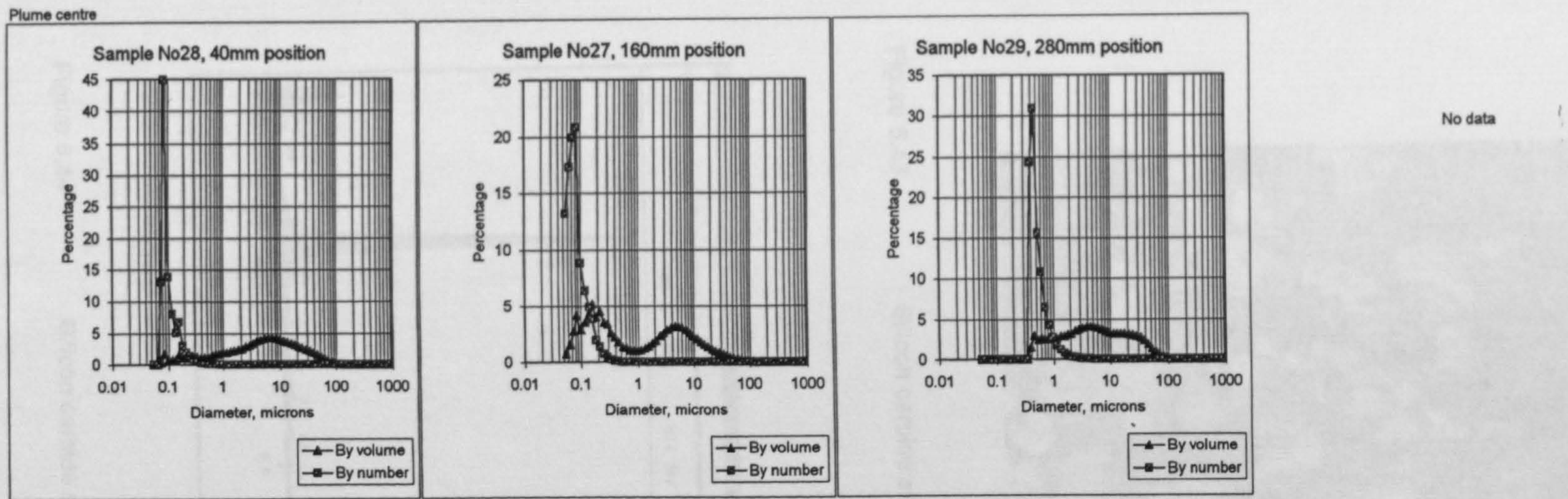


Figure 5.41 2% silicon carbide Heavyweight motor particle size distribution (firing 6)

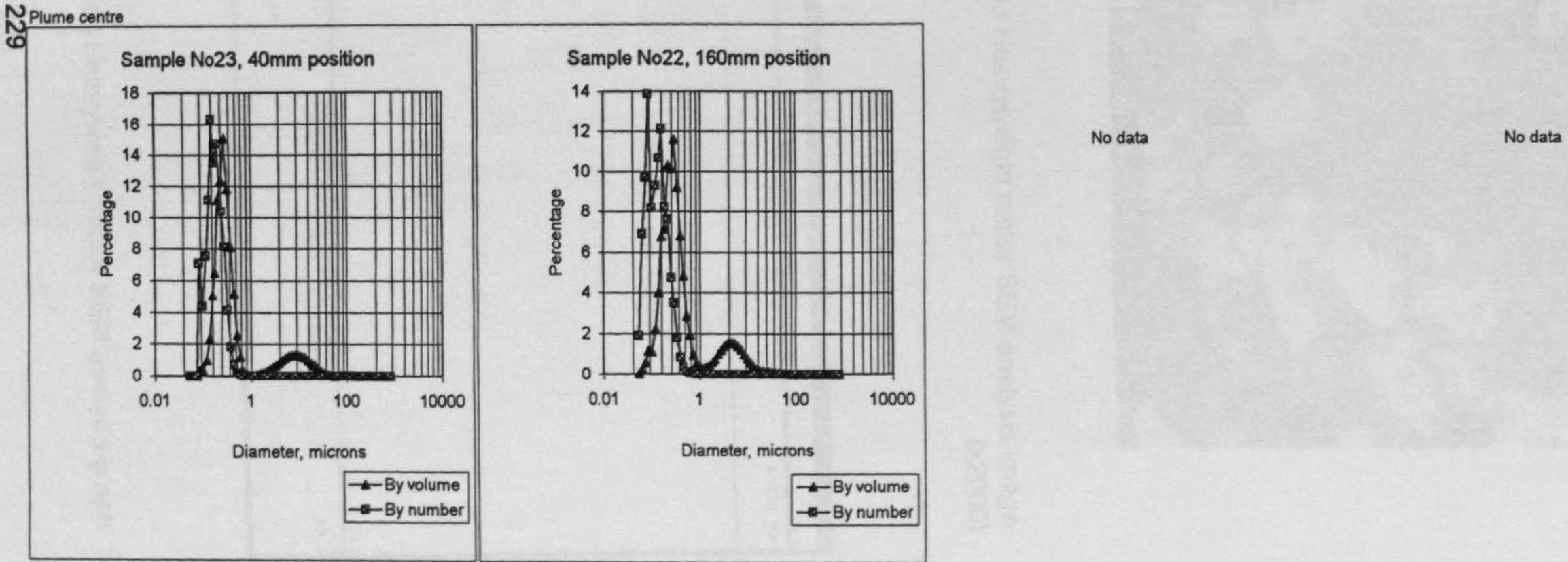


Figure 5.42 Unseeded Heavyweight motor particle size distribution (firing 5)

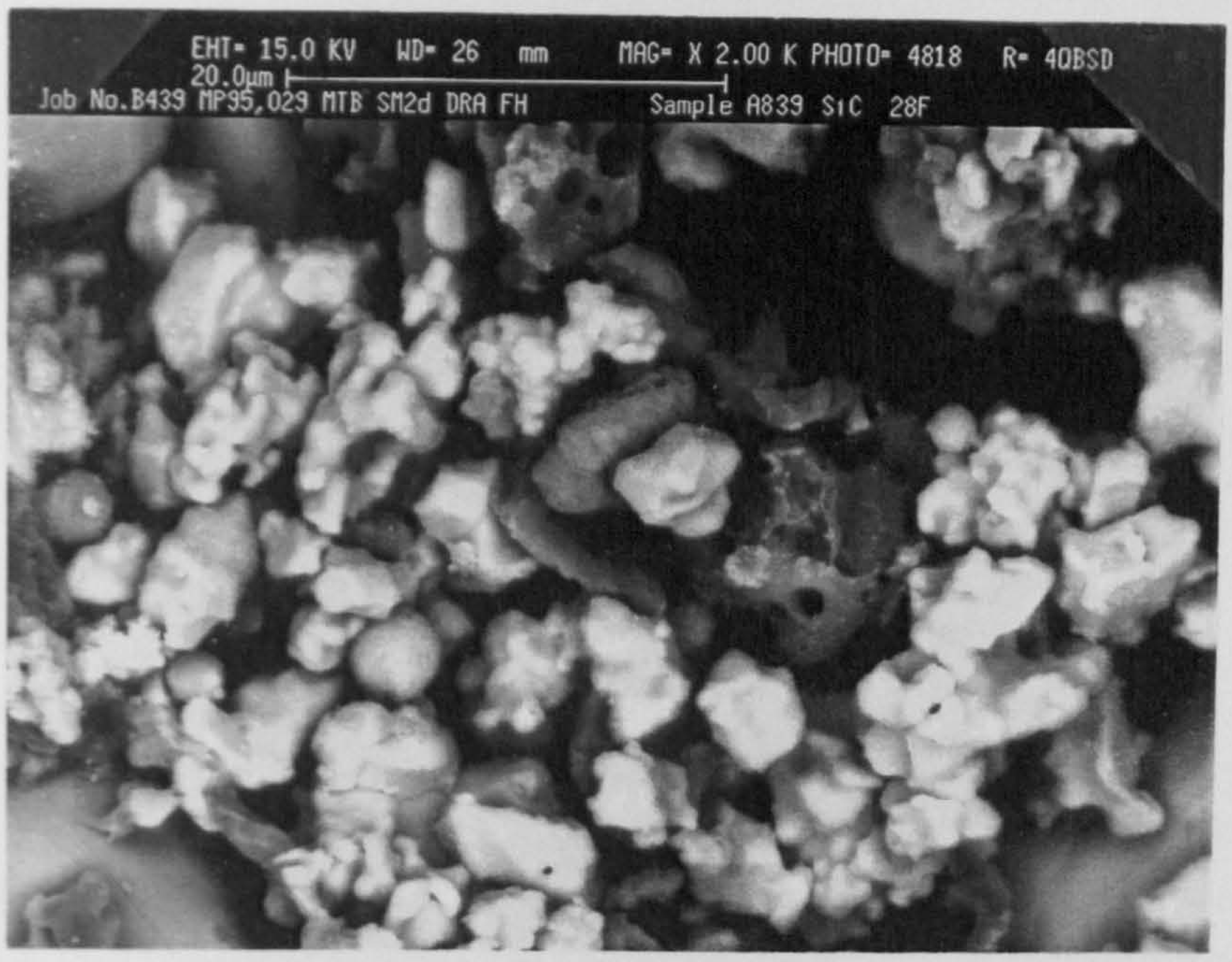


Figure 5.43 Silicon carbide seeded Heavyweight motor SEM analysis image (x2000)

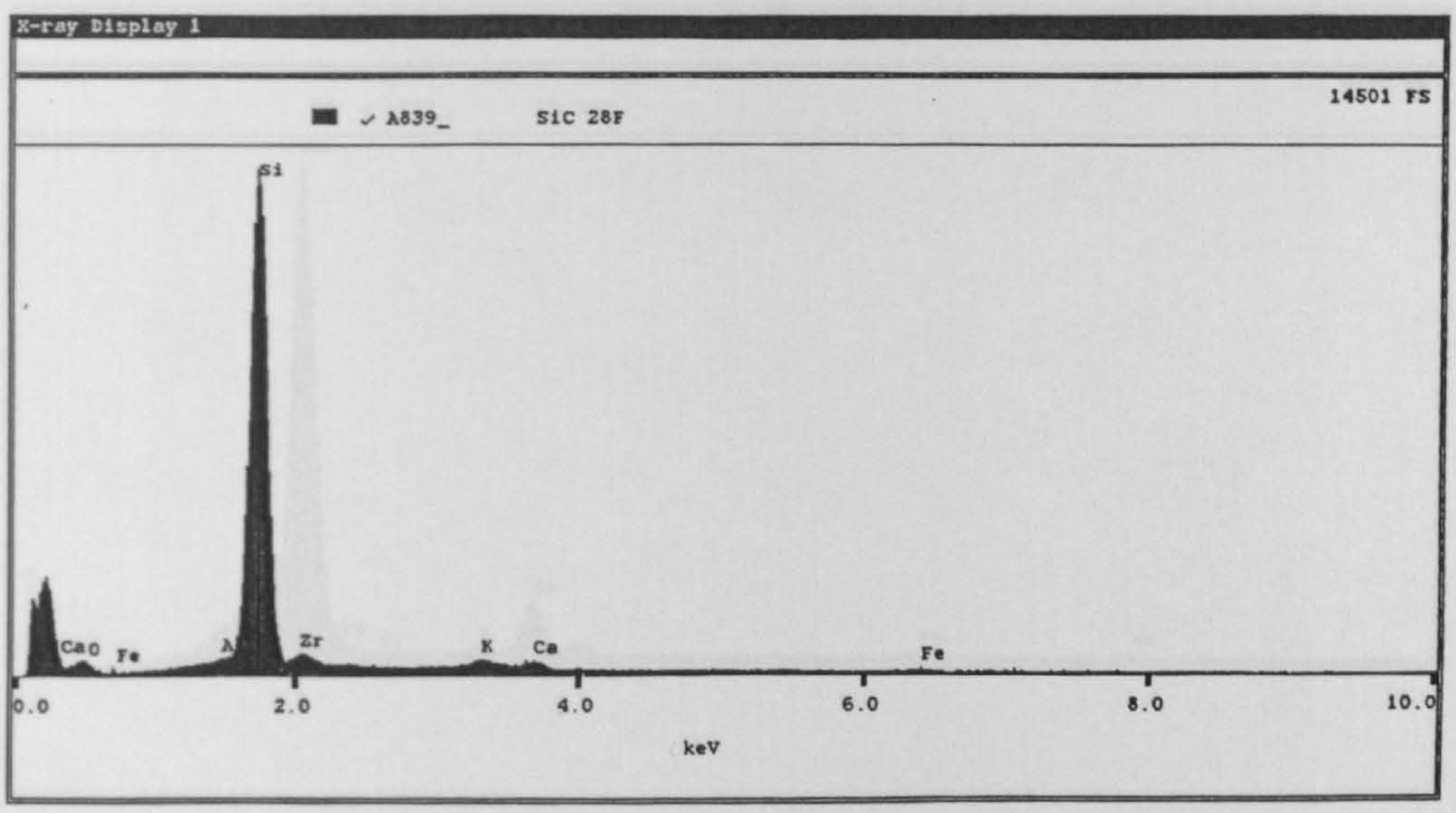


Figure 5.44 Silicon carbide seeded Heavyweight motor SEM analysis graph

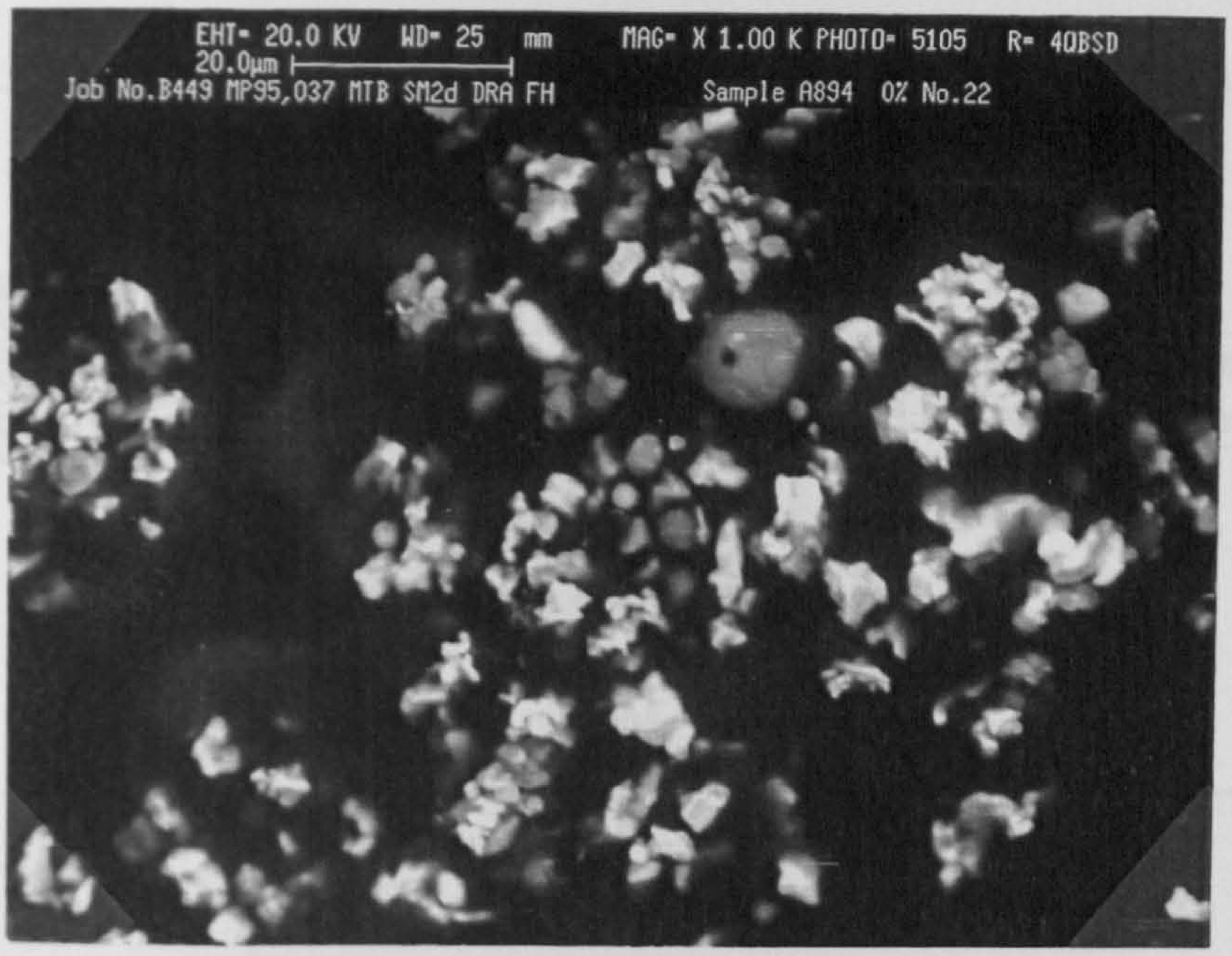


Figure 5.45 Unseeded Heavyweight motor SEM analysis image (x1000)

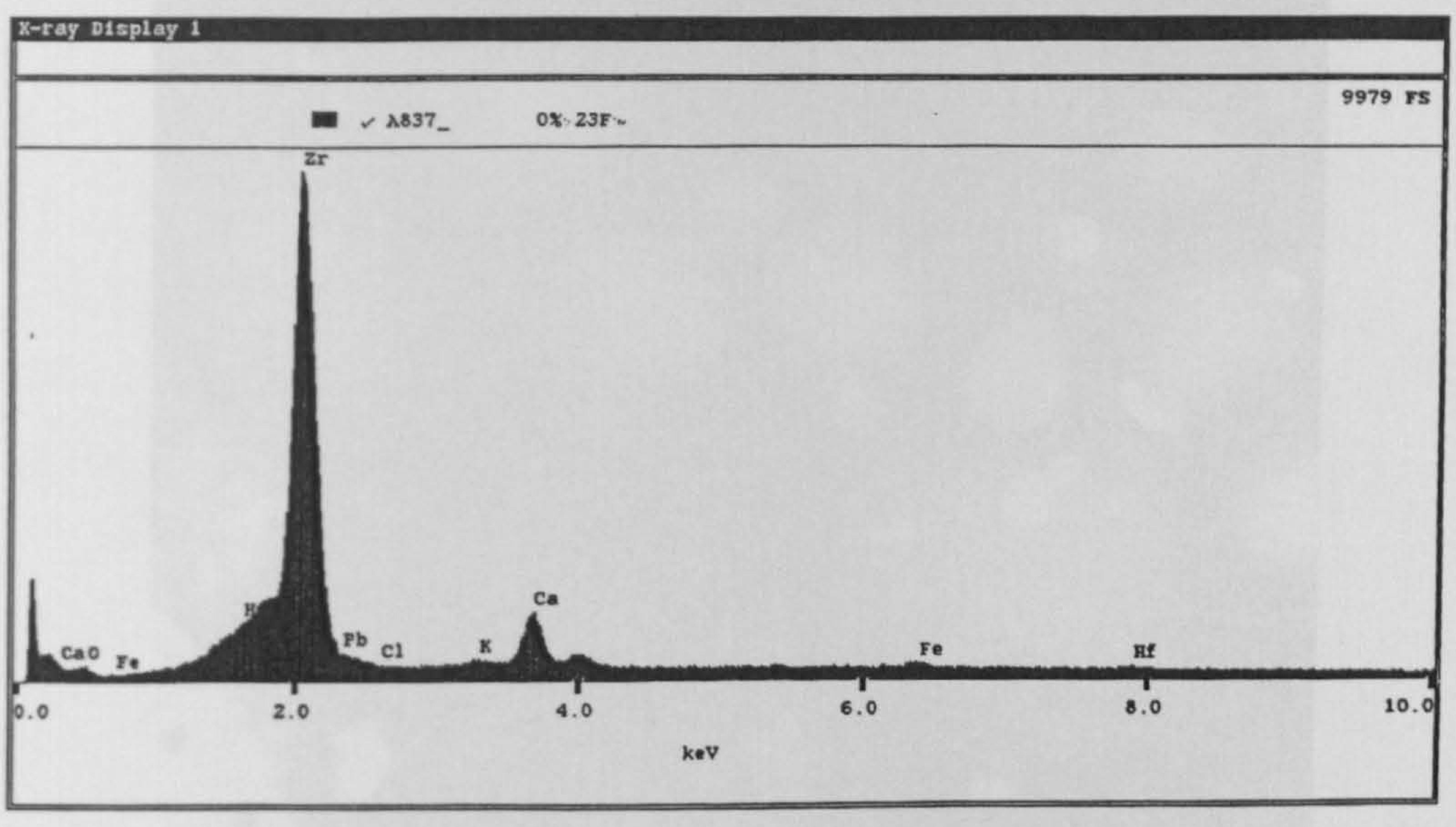


Figure 5.46 Unseeded Heavyweight motor SEM analysis graph

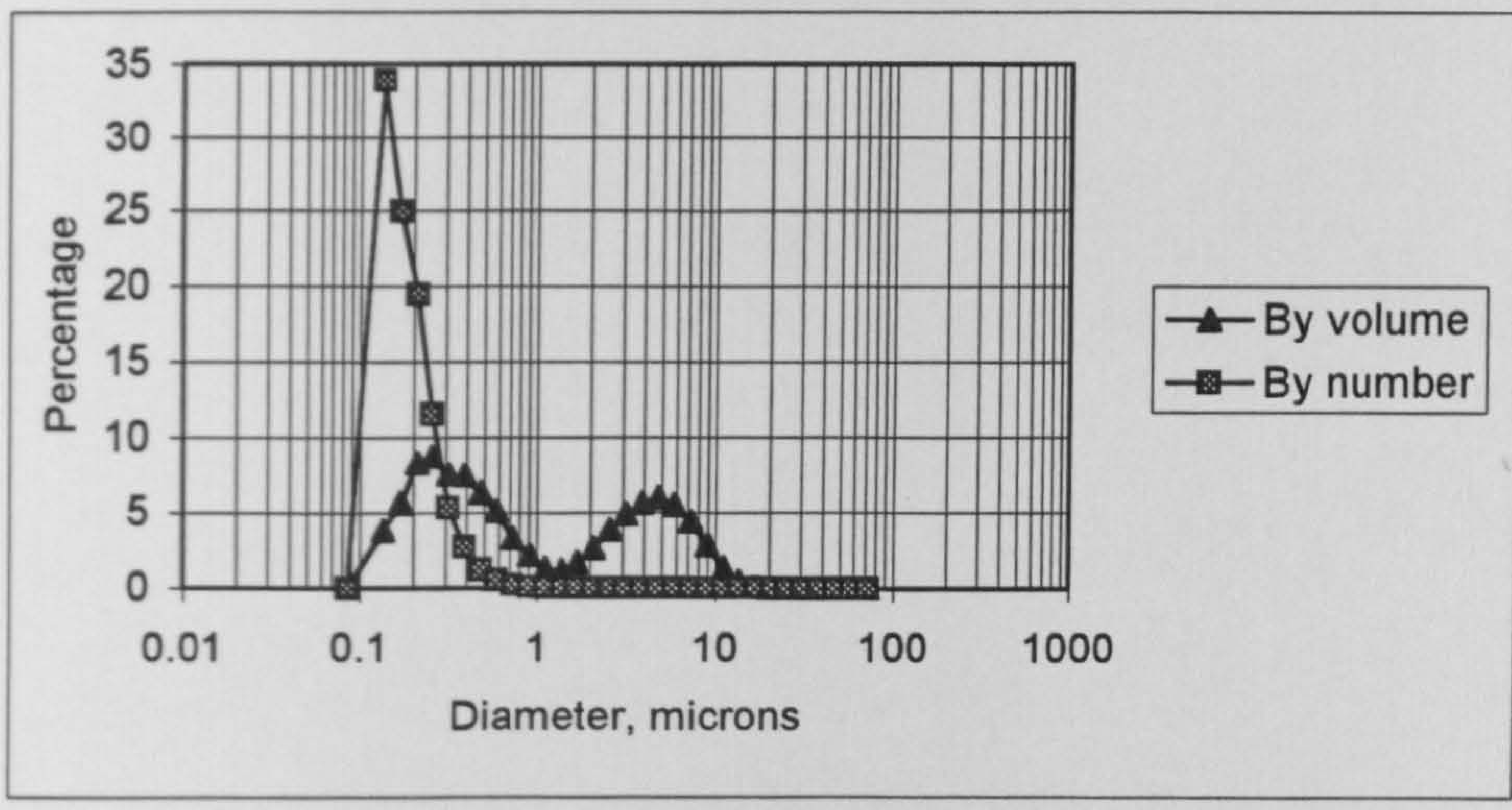


Figure 5.47 Particle size distribution for Experimental Aluminised Composite motor

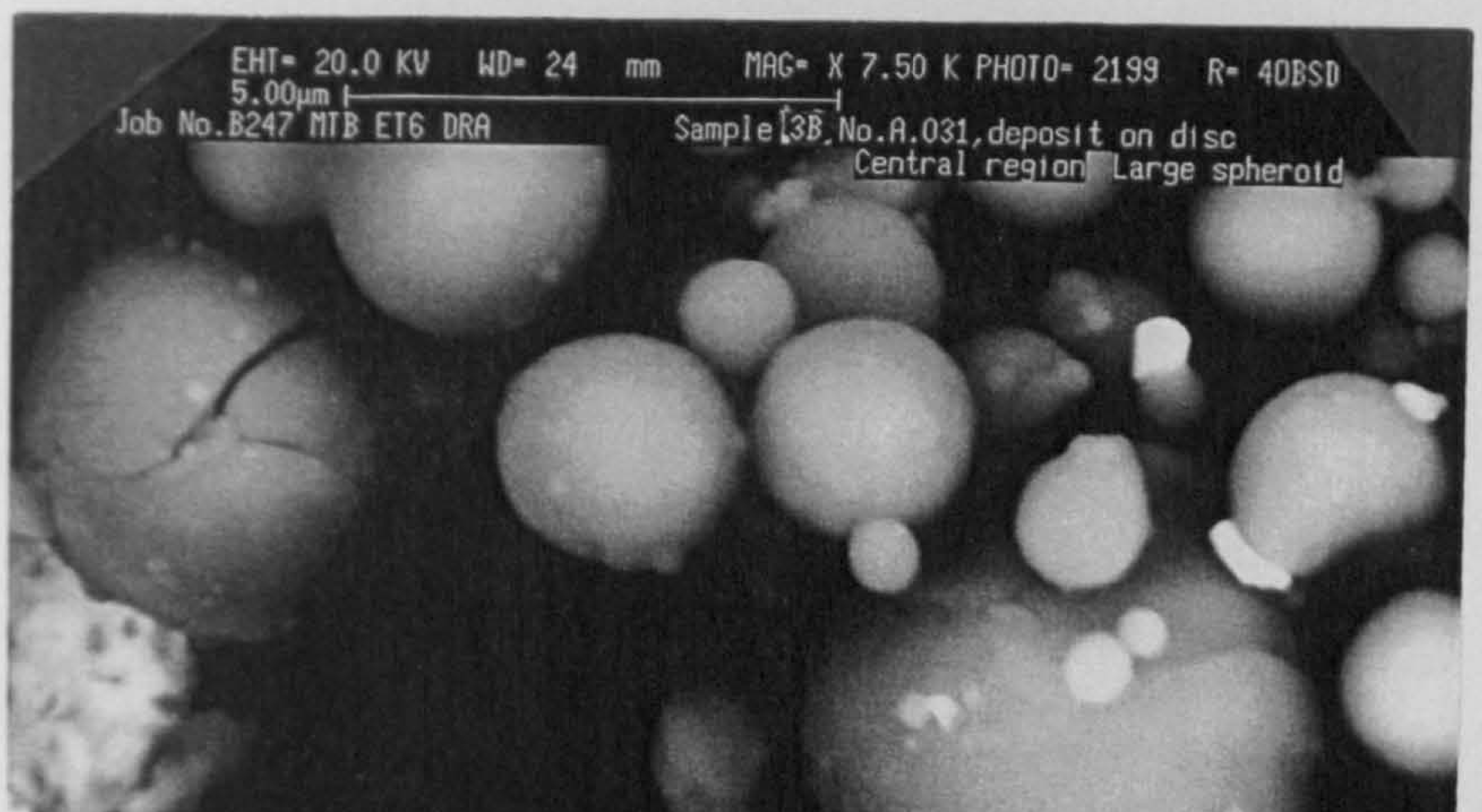
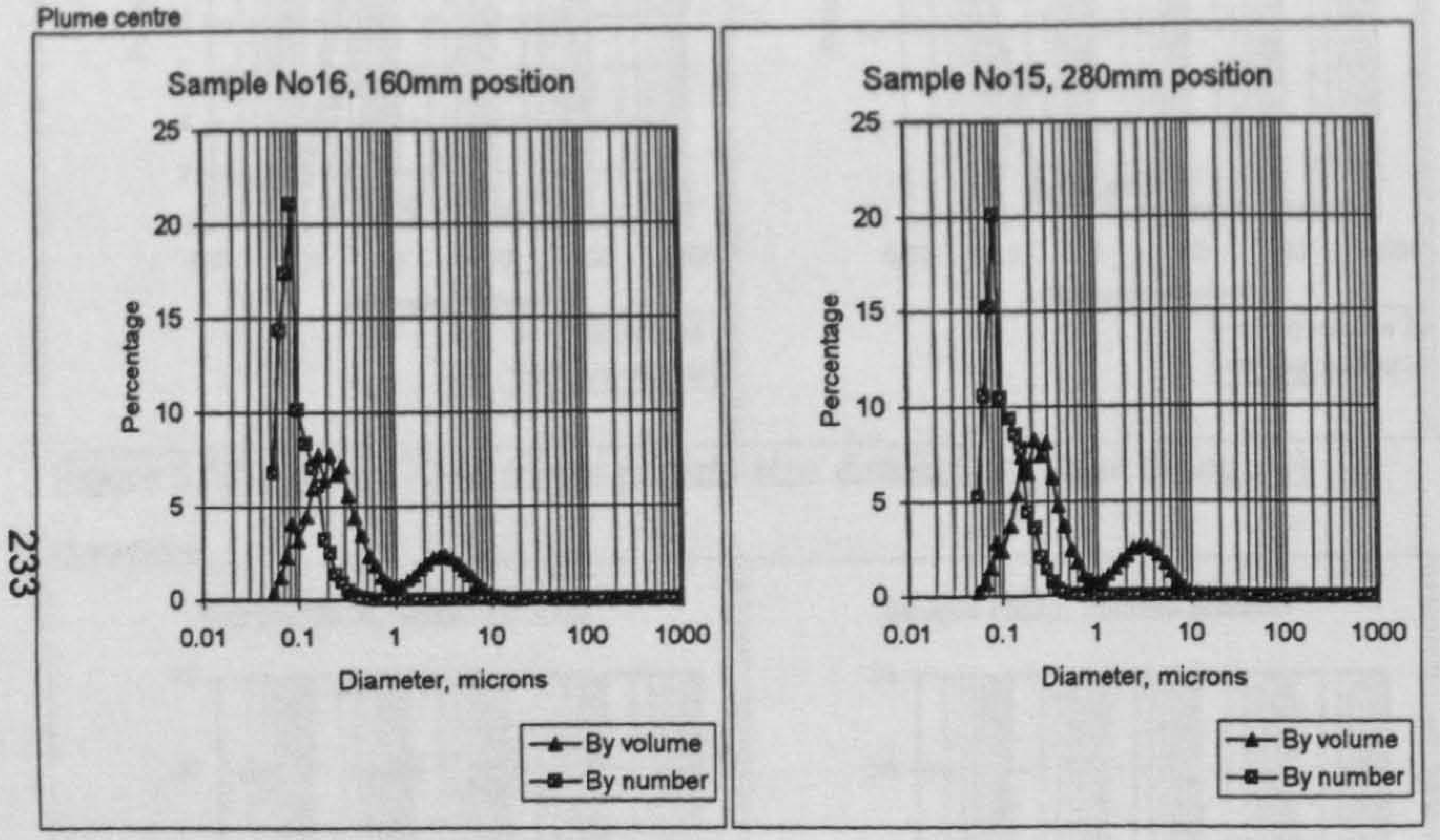


Figure 5.48 Experimental Aluminised Composite motor SEM analysis image (x7500)

Plume centre



No data

No data

No 80mm data

Figure 5.49 CRV7 C14 motor particle size distribution, 1.5m (firing 13)

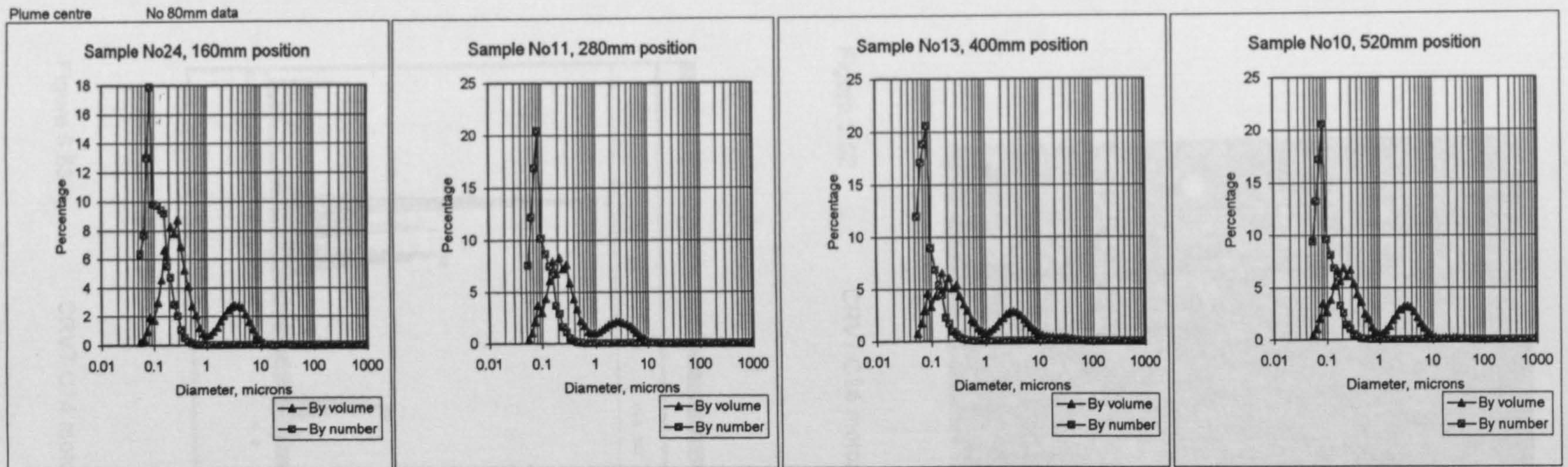


Figure 5.50 CRV7 C14 motor particle size distribution, 2.5m (firing 10)

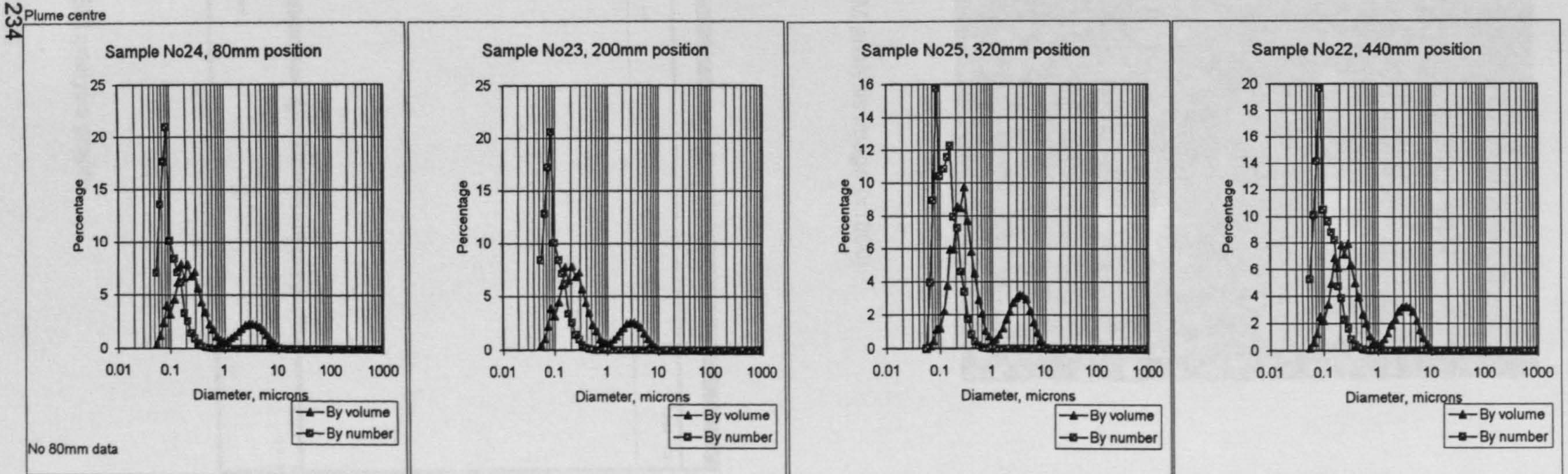


Figure 5.51 CRV7 C14 motor particle size distribution, 2.5m (firing 11)

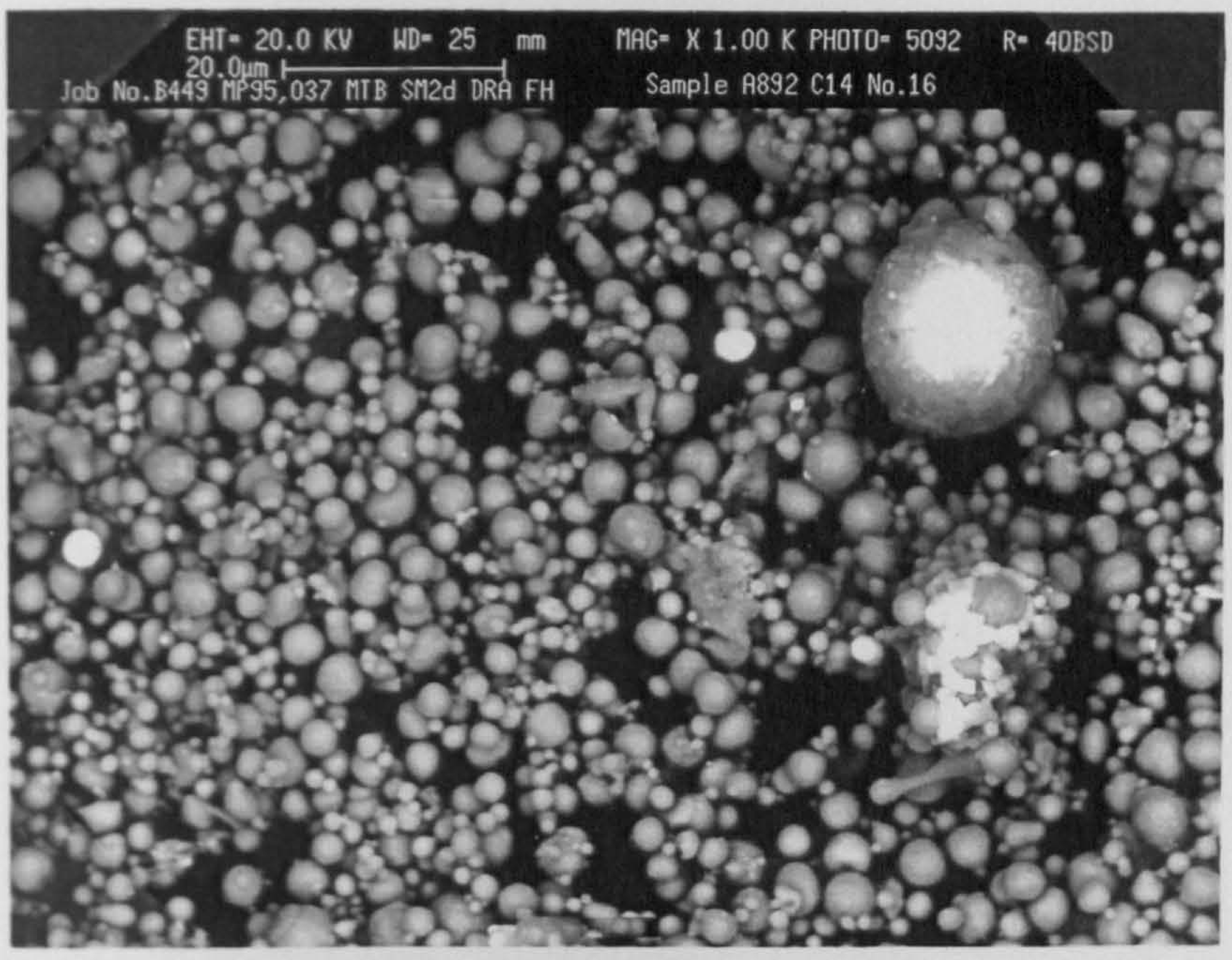


Figure 5.52 CRV7 C14 motor SEM analysis image (x1000)

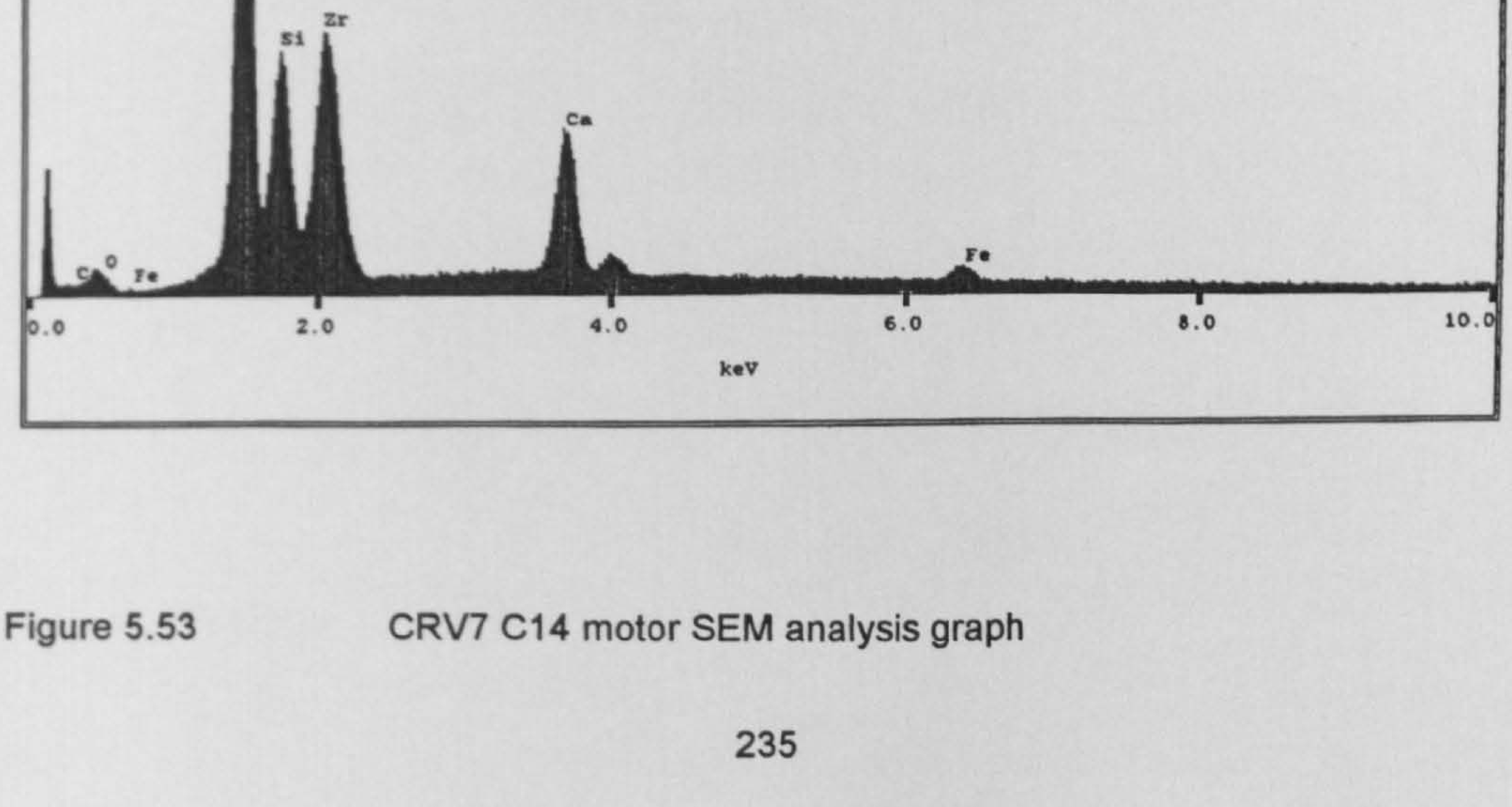
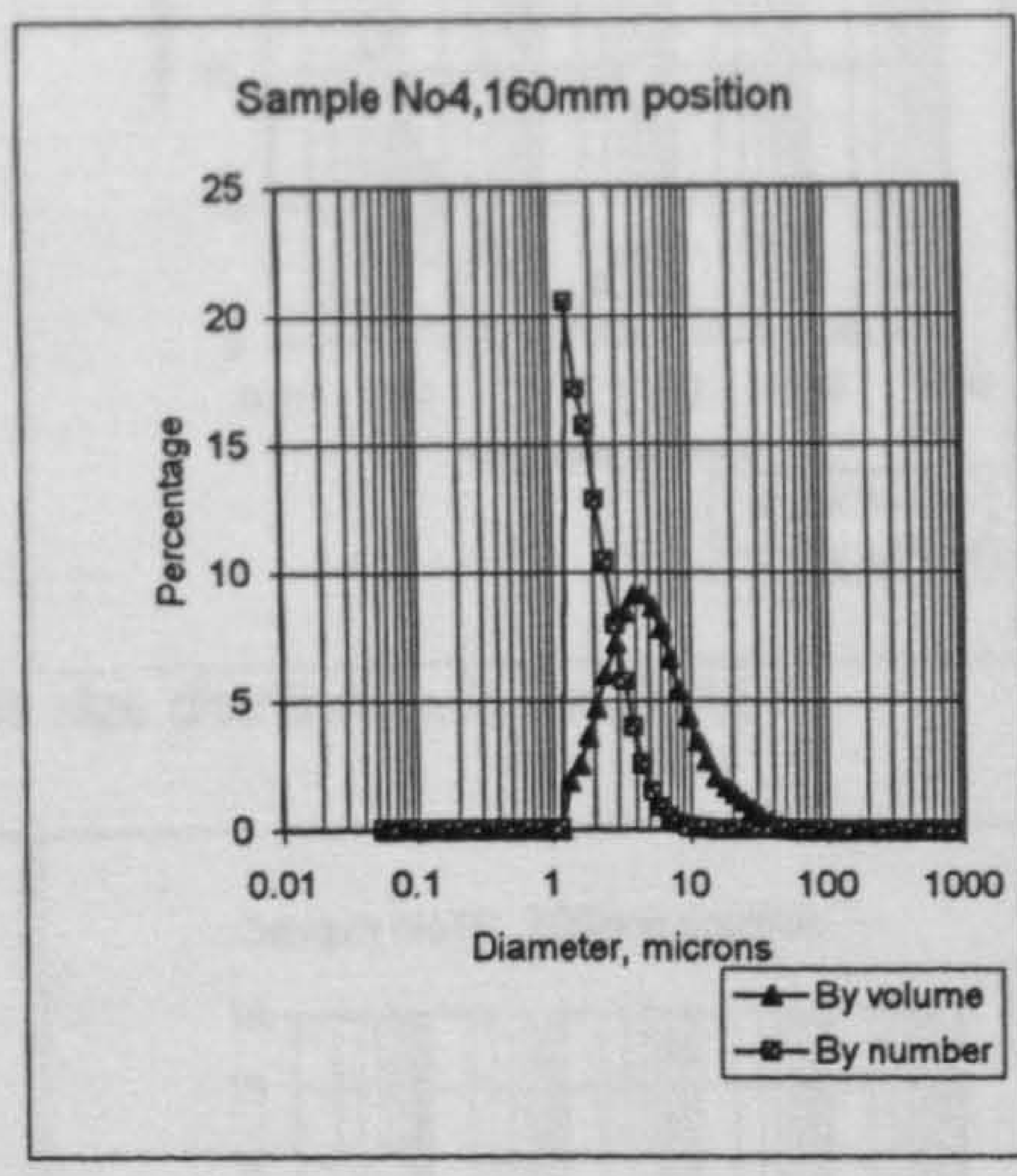
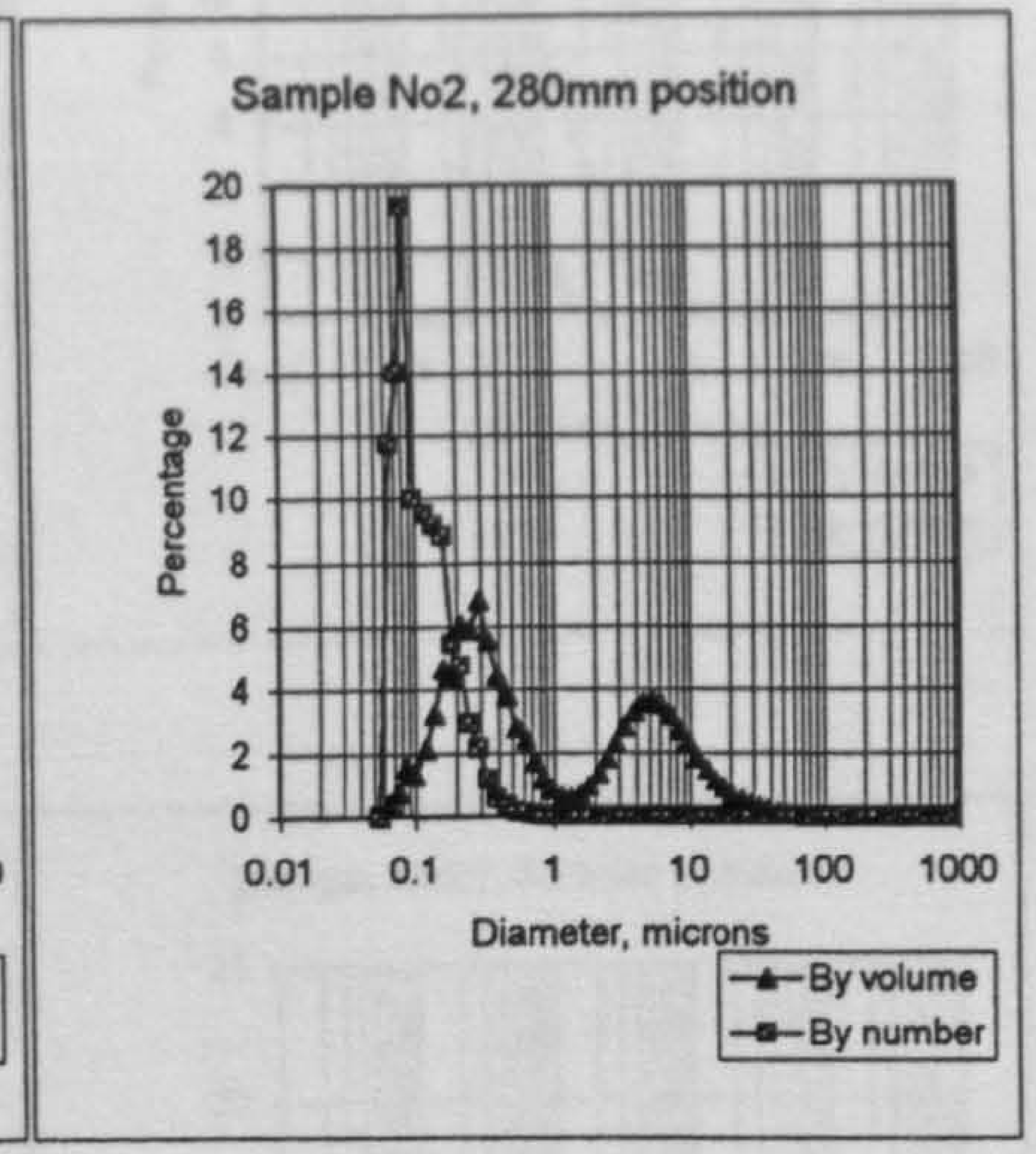


Figure 5.53 CRV7 C14 motor SEM analysis graph

Plume centre

No data





No data

Figure 5.54 CRV7 C15 motor particle size distribution, 1.5m (firing 8)

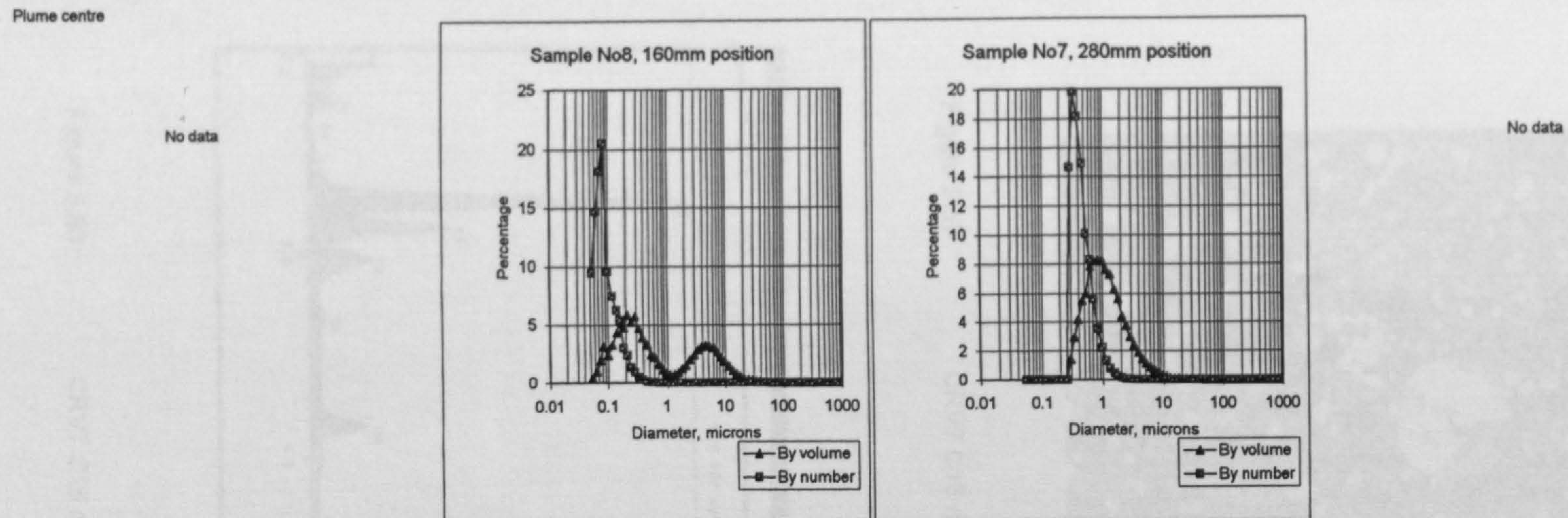


Figure 5.55 CRV7 C15 motor particle size distribution, 2.5m (firing 9)

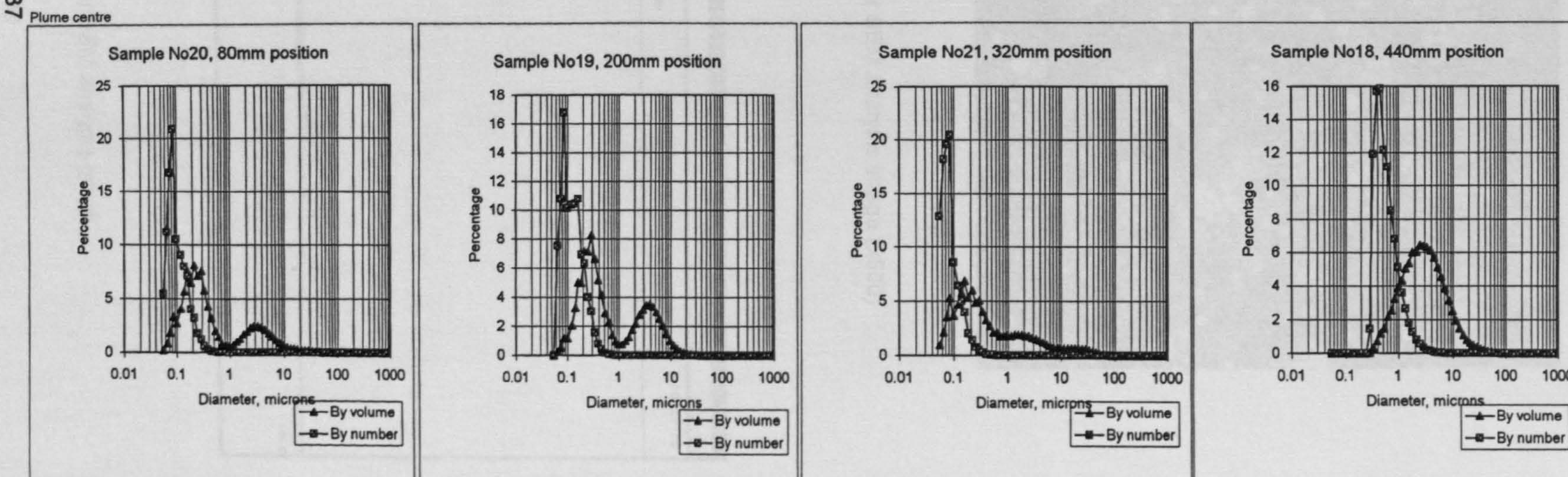


Figure 5.56 CRV7 C15 motor particle size distribution, 2.5m (firing 12)

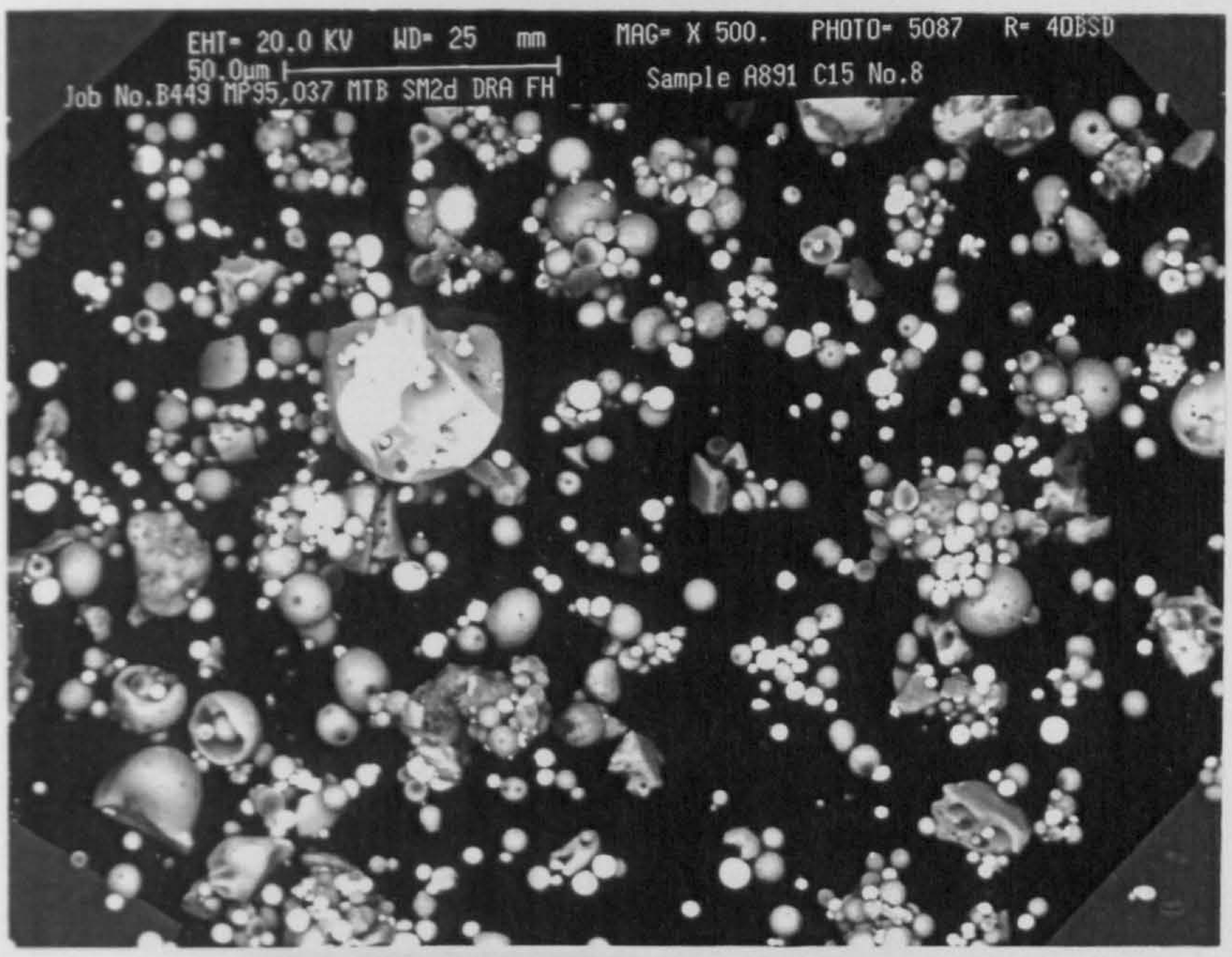


Figure 5.57 CRV7 C15 motor SEM analysis image (x500)

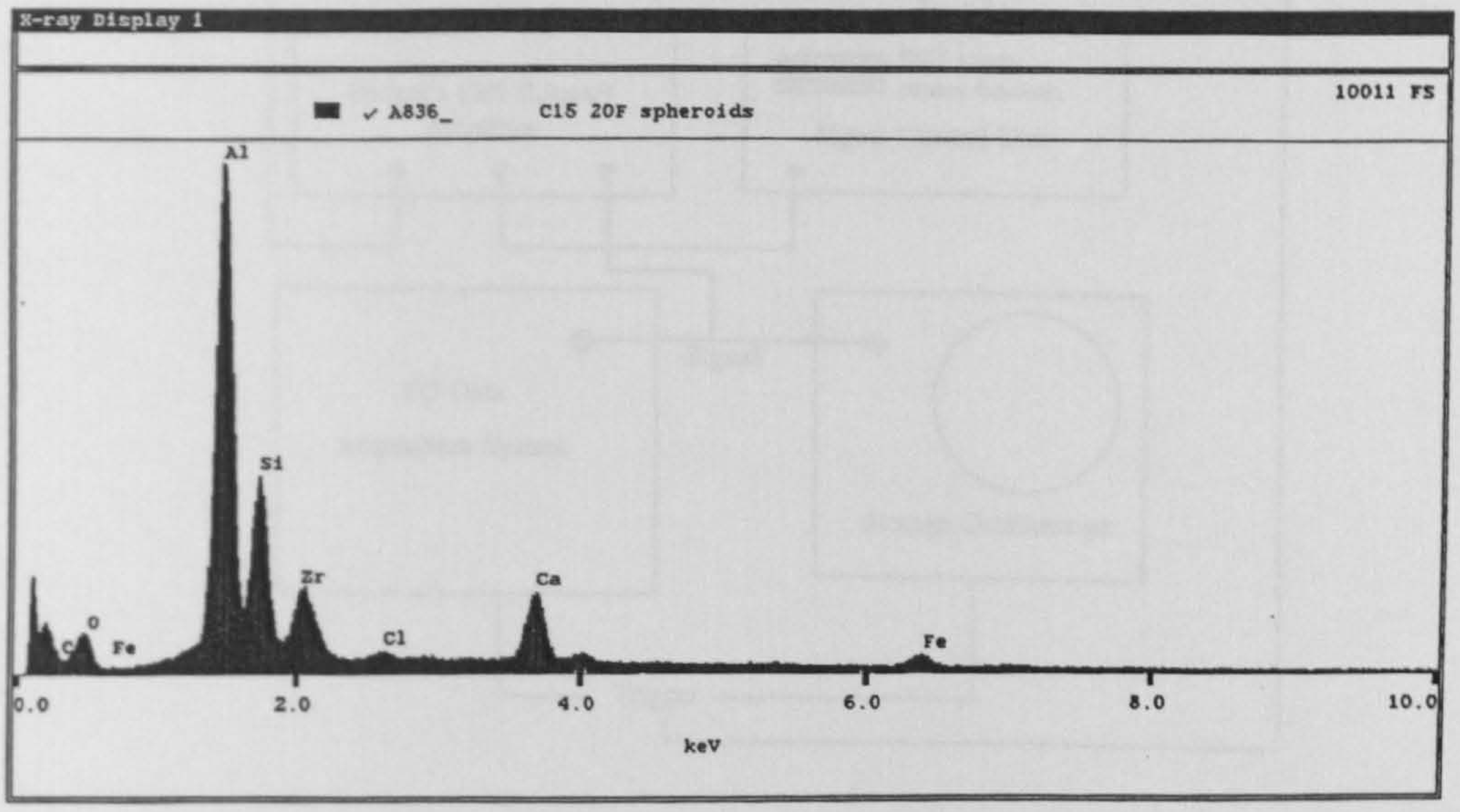


Figure 5.58 CRV7 C15 motor SEM analysis graph

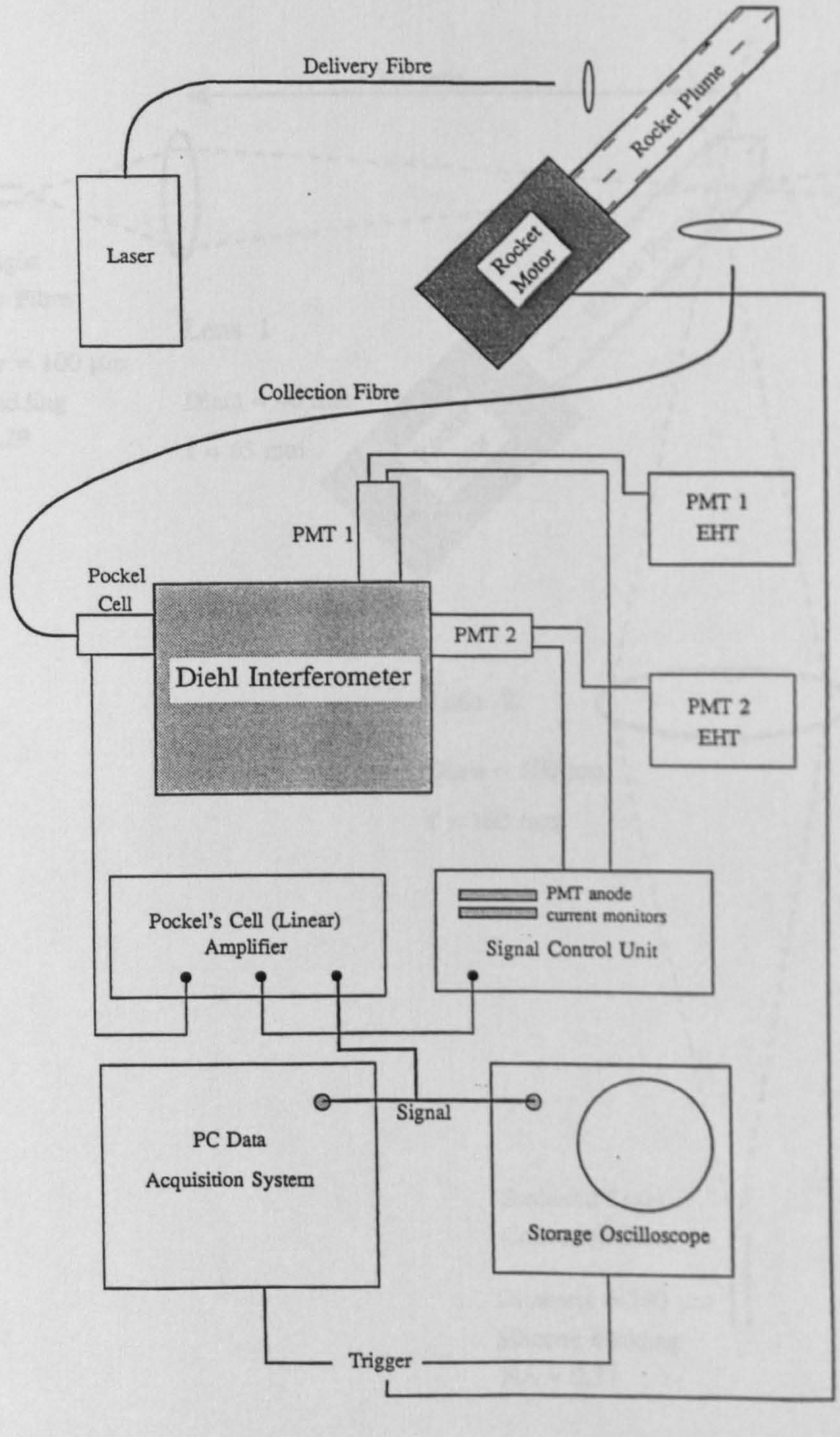


Figure 6.1 Schematic of Michelson interferometer system

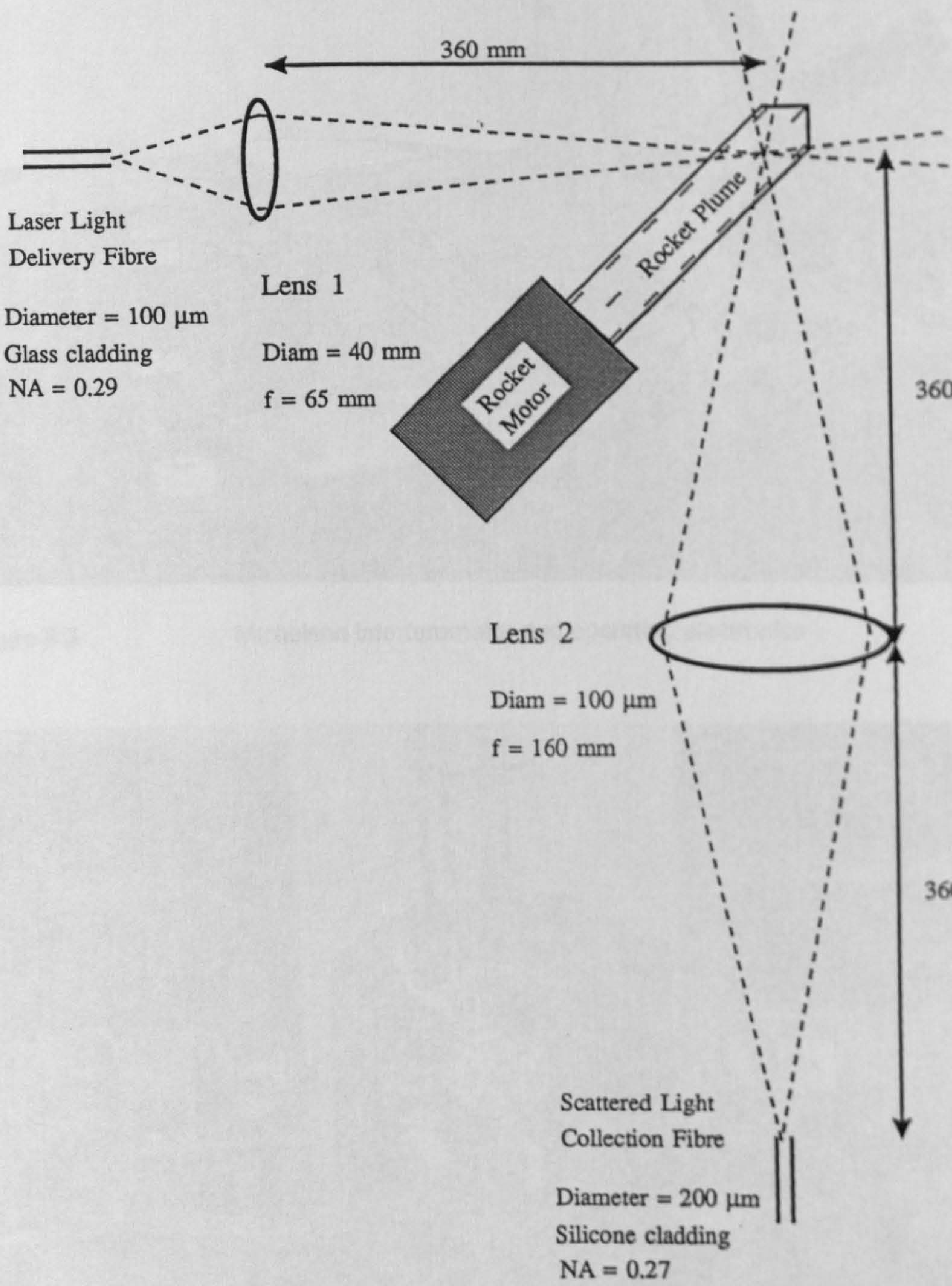


Figure 6.2 Schematic of the Michelson interferometer's optical arrangement

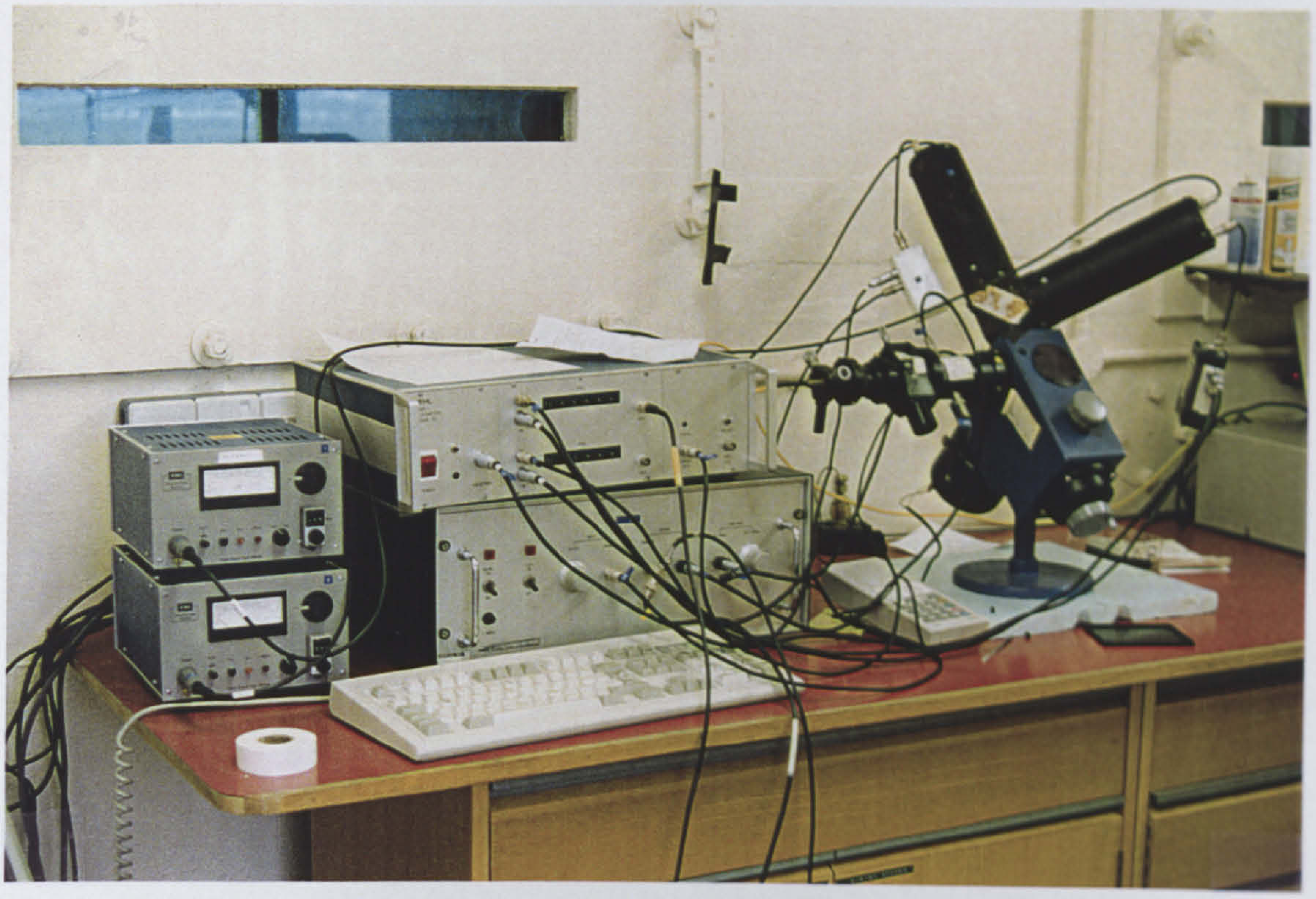


Figure 6.3 Michelson interferometer and operating electronics

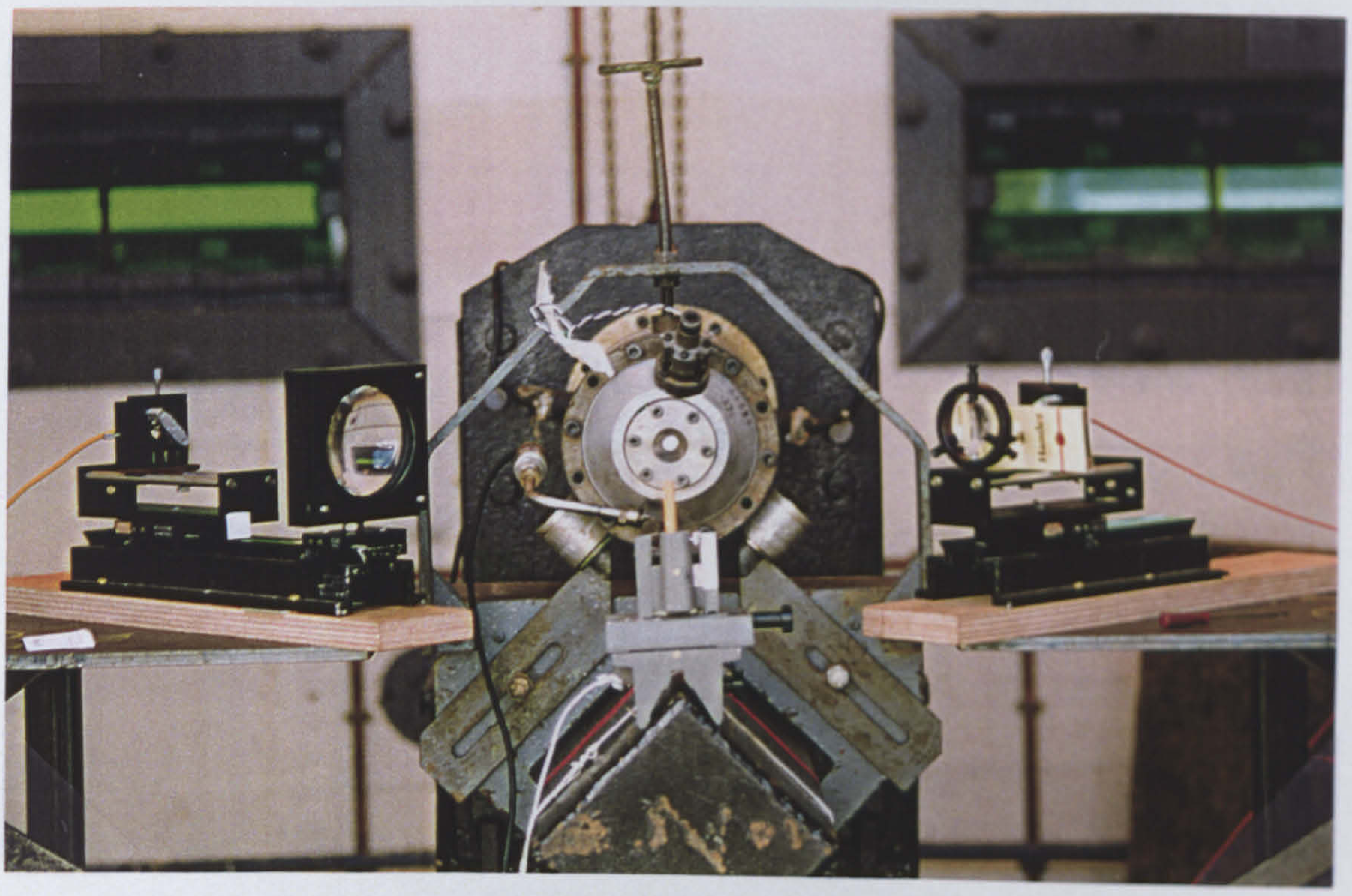


Figure 6.4 Delivery and collection optics positioned around a Heavyweight motor

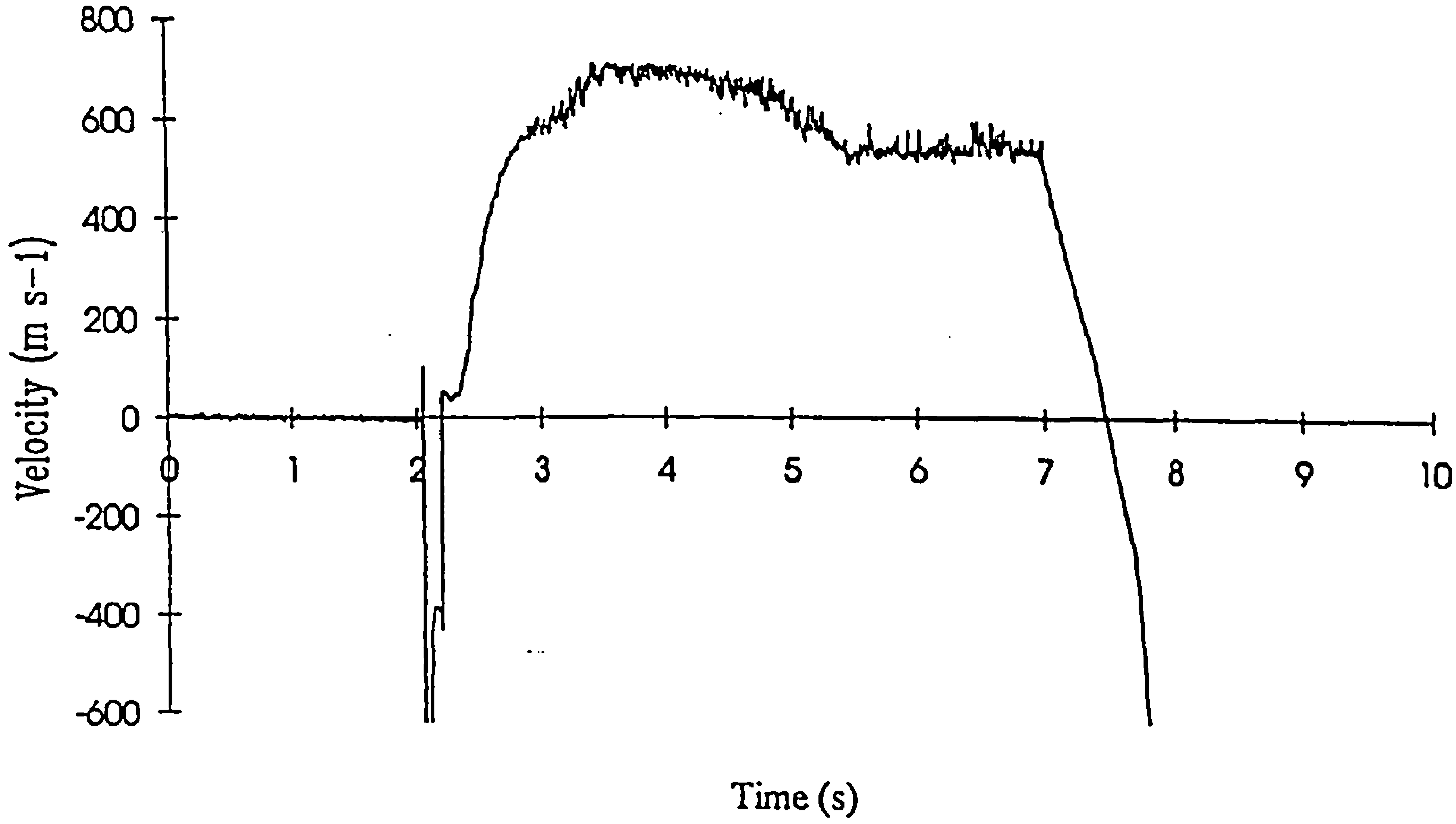


Figure 6.5 Velocity time profile for Firing 1 (CDB motor)

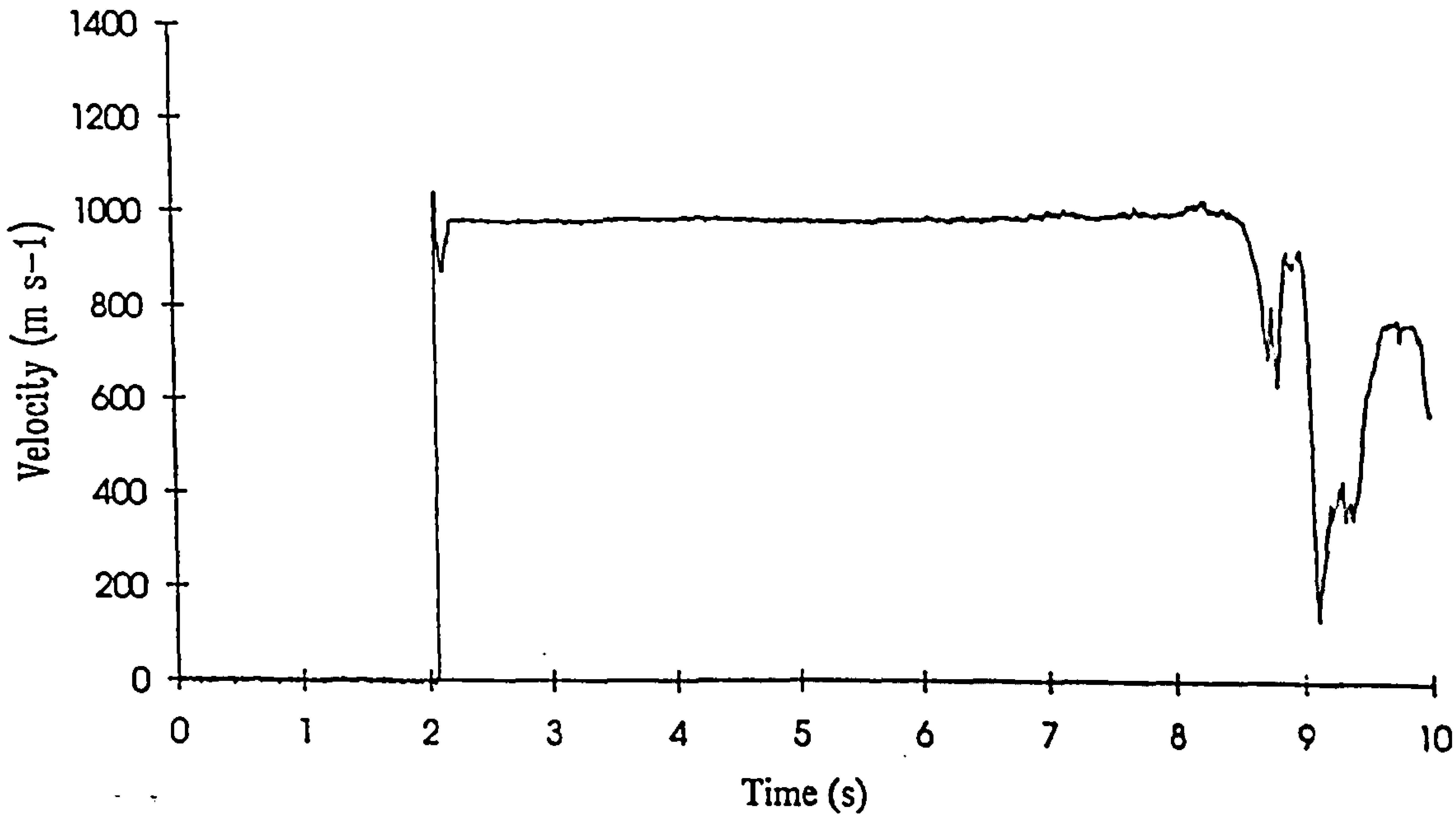


Figure 6.6 Velocity time profile for Firing 2 (Heavyweight with 2% zirconia)

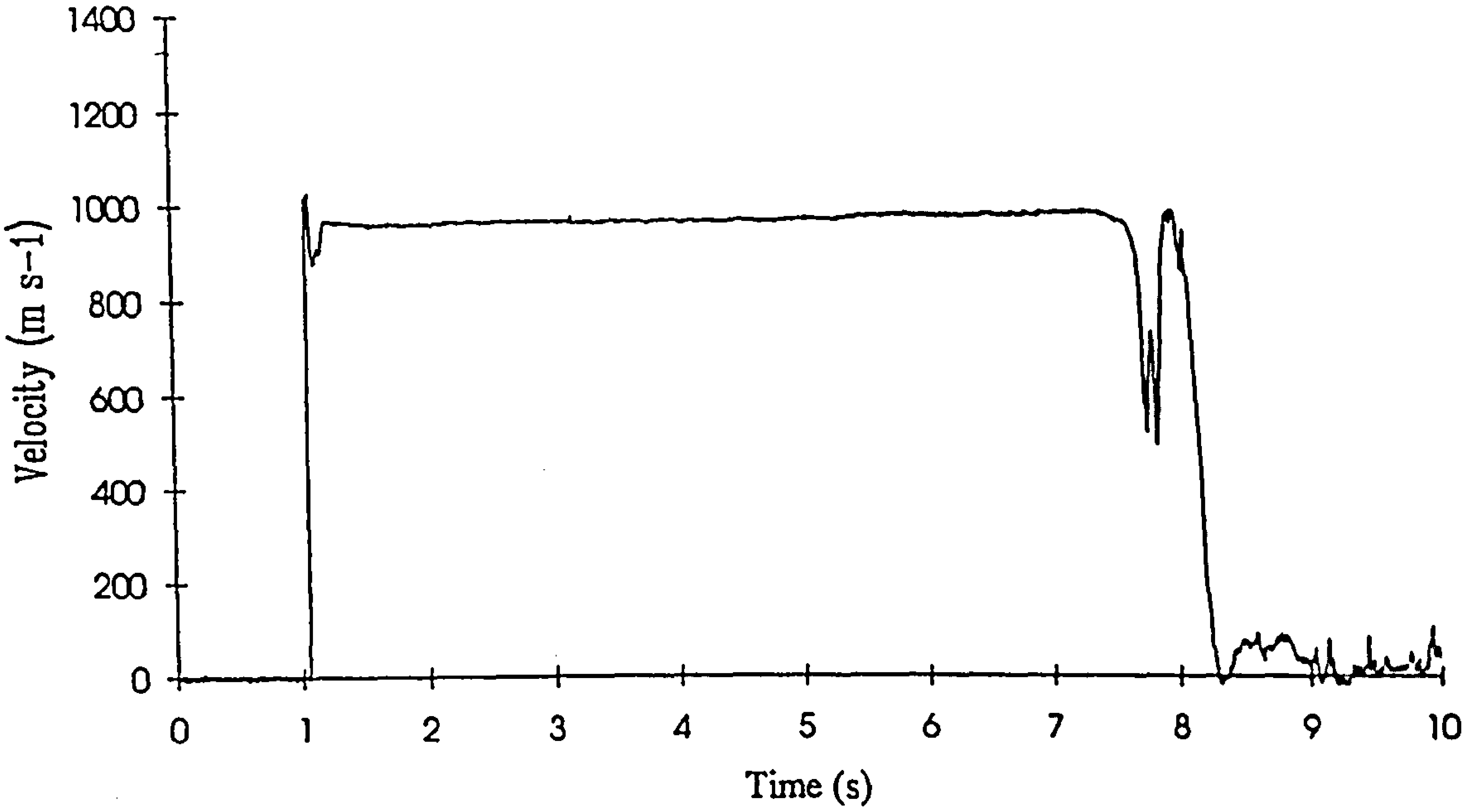


Figure 6.7 Velocity time profile for Firing 3 (Heavyweight with 2% zirconia)

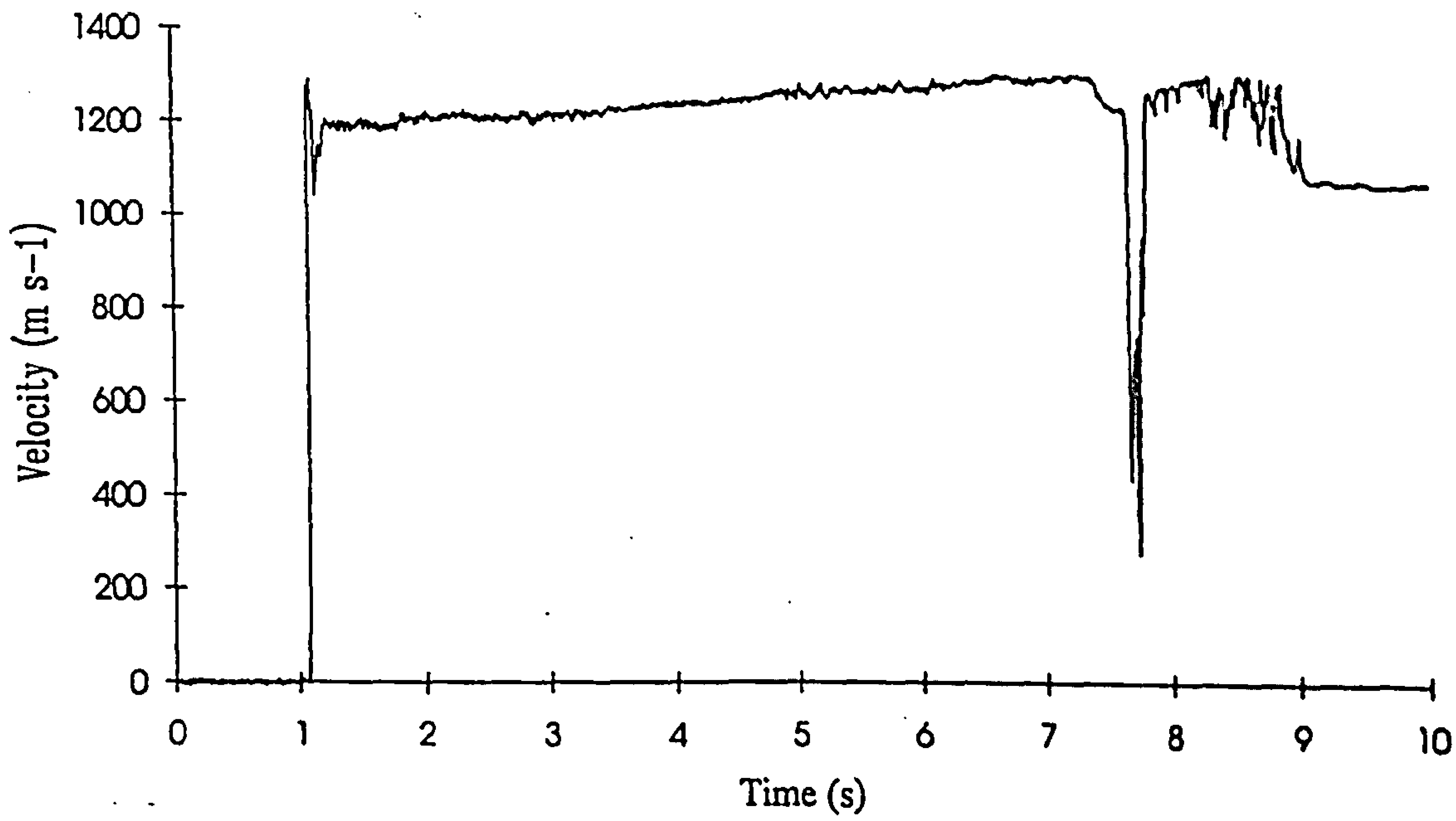


Figure 6.8 Velocity time profile for Firing 4 (Heavyweight with 1% zirconia)

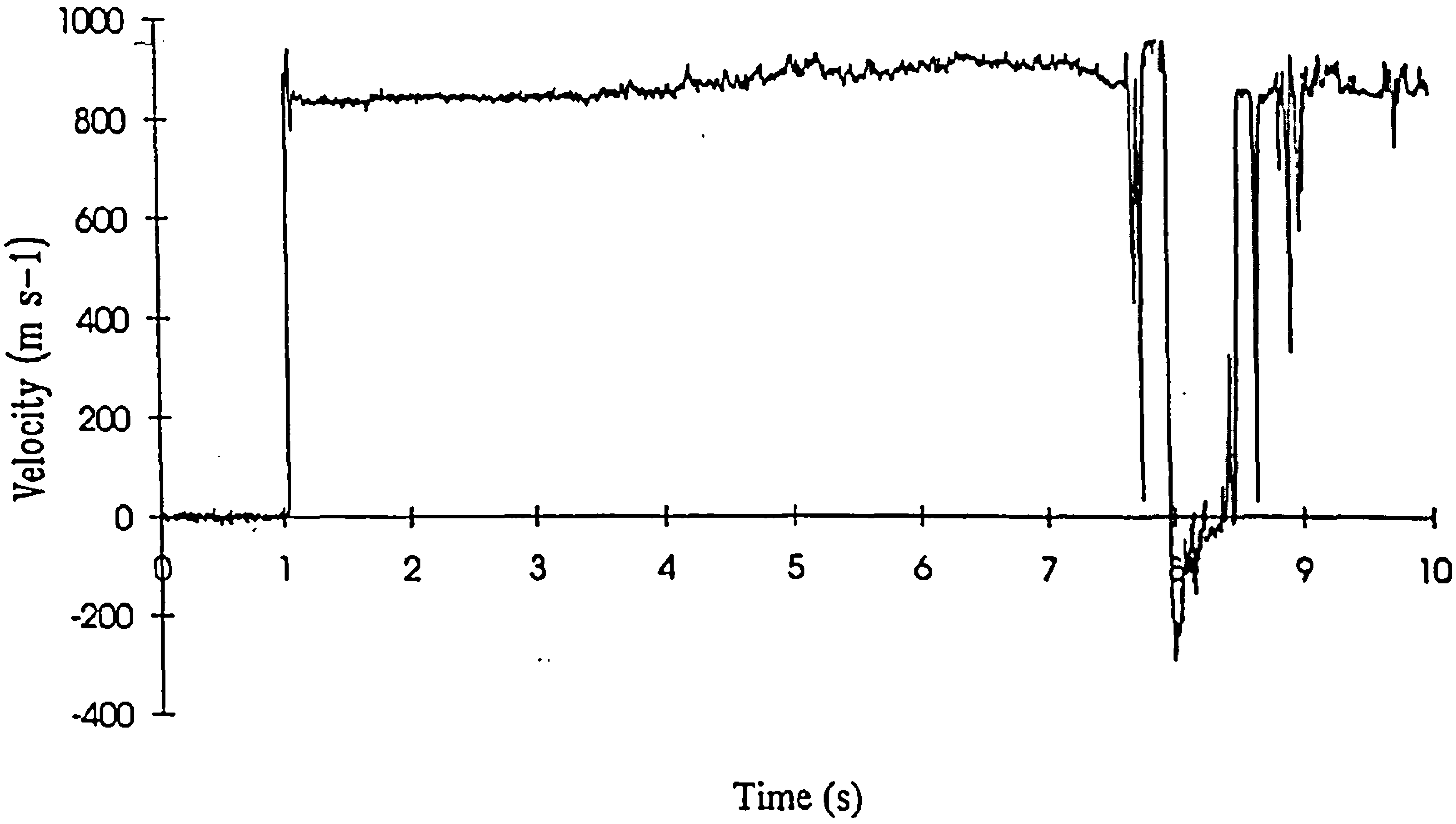


Figure 6.9 Velocity time profile for Firing 5 (Heavyweight with no seeding)

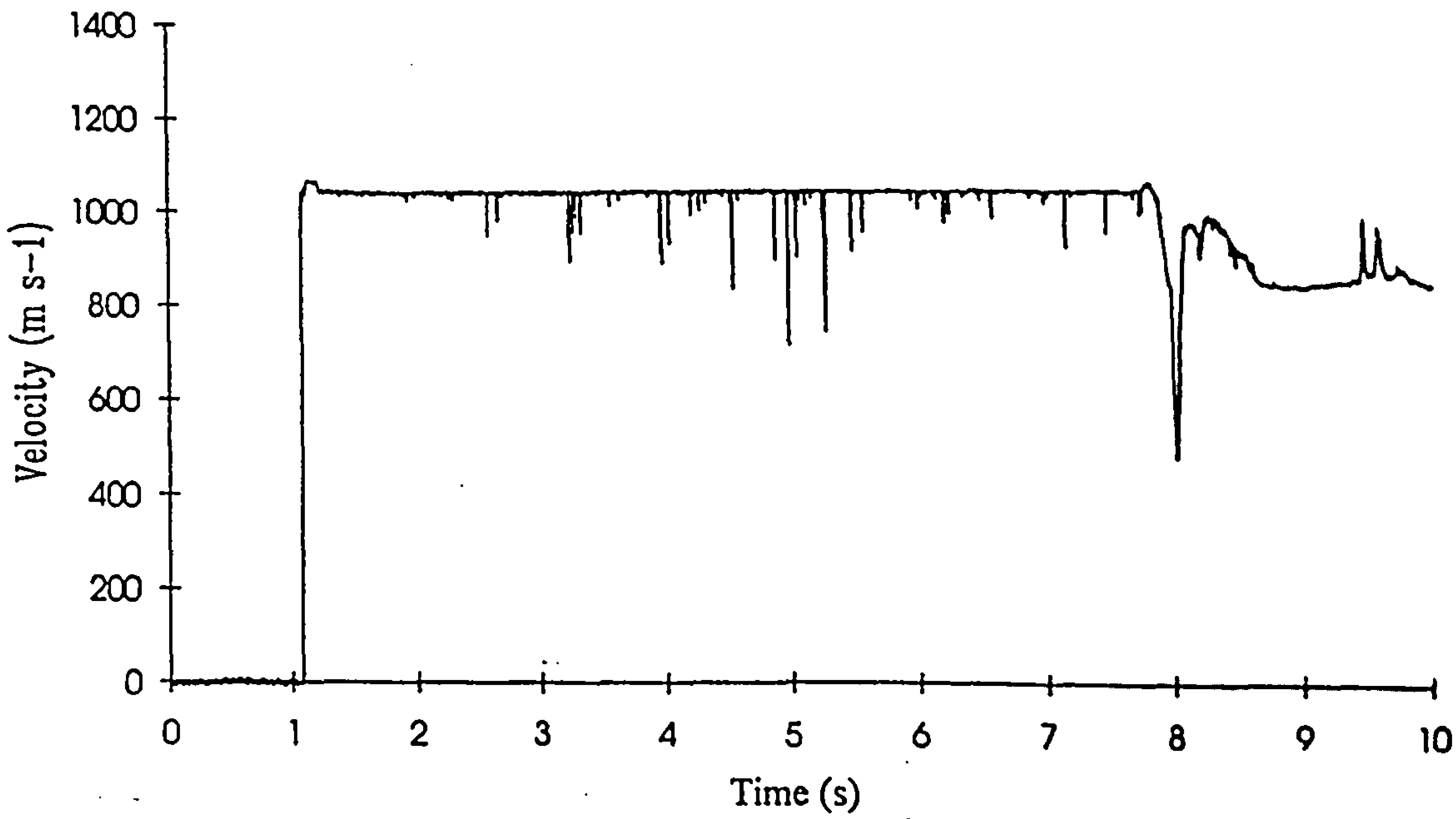


Figure 6.10 Velocity time profile for Firing 6 (Heavyweight with 2% silicon carbide)

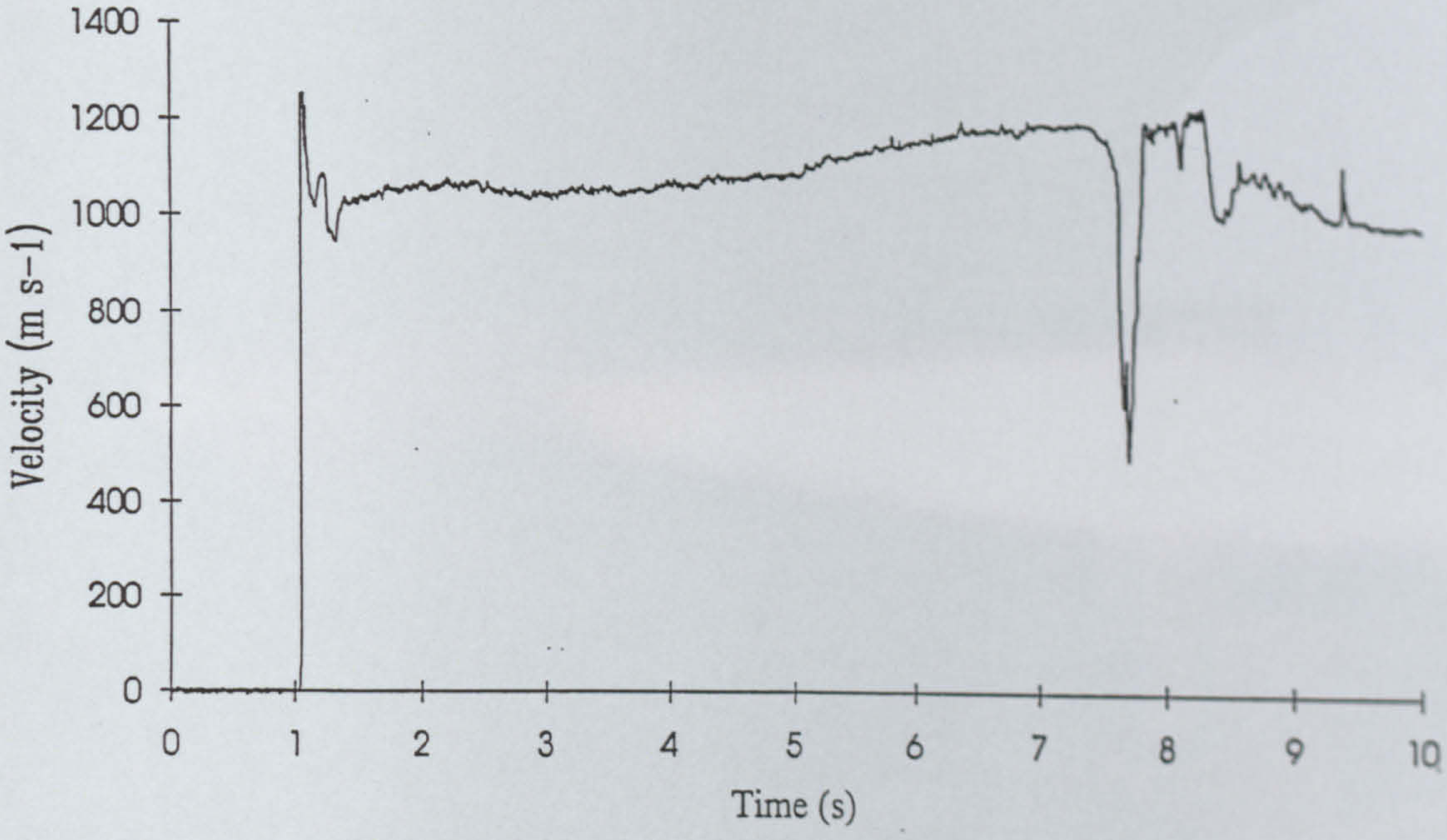


Figure 6.11 Velocity time profile for Firing 7 (Heavyweight with 1% zirconia)

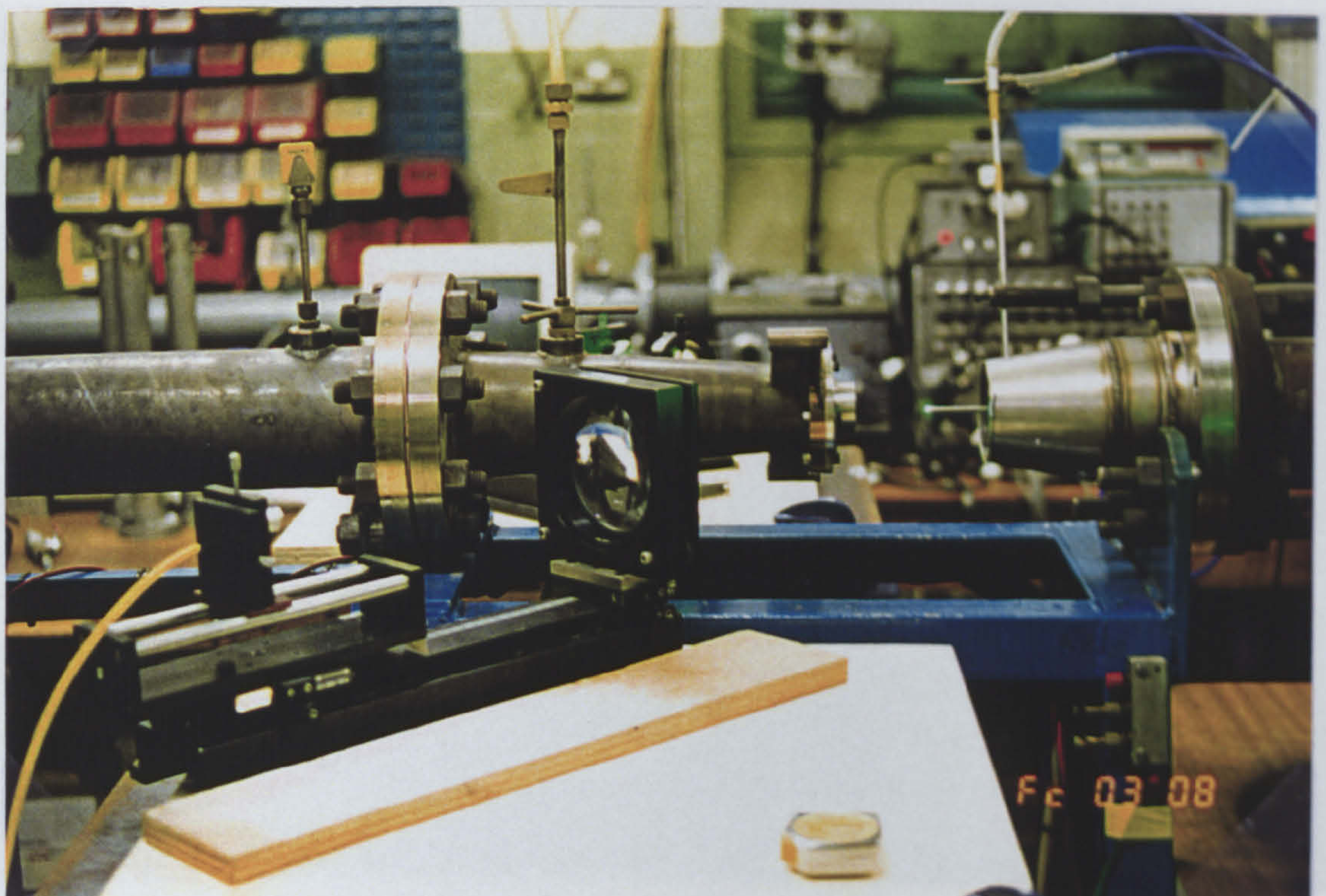


Figure 6.12 Experimental set-up for measurement of the controllable high speed flow

Figure 6.13 CDB motor firing

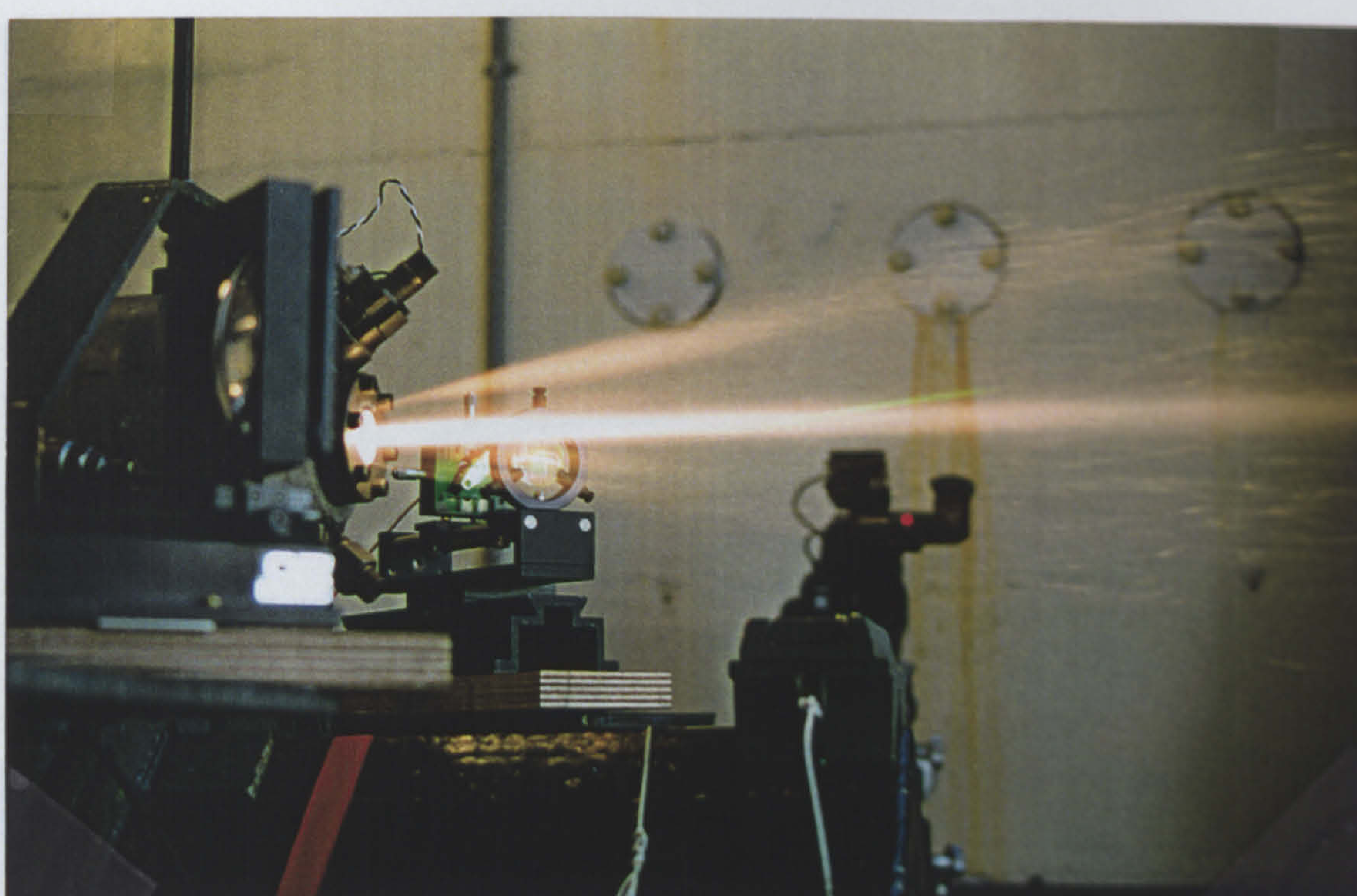


Figure 6.14 Heavyweight motor firing (1% zirconia seeding)

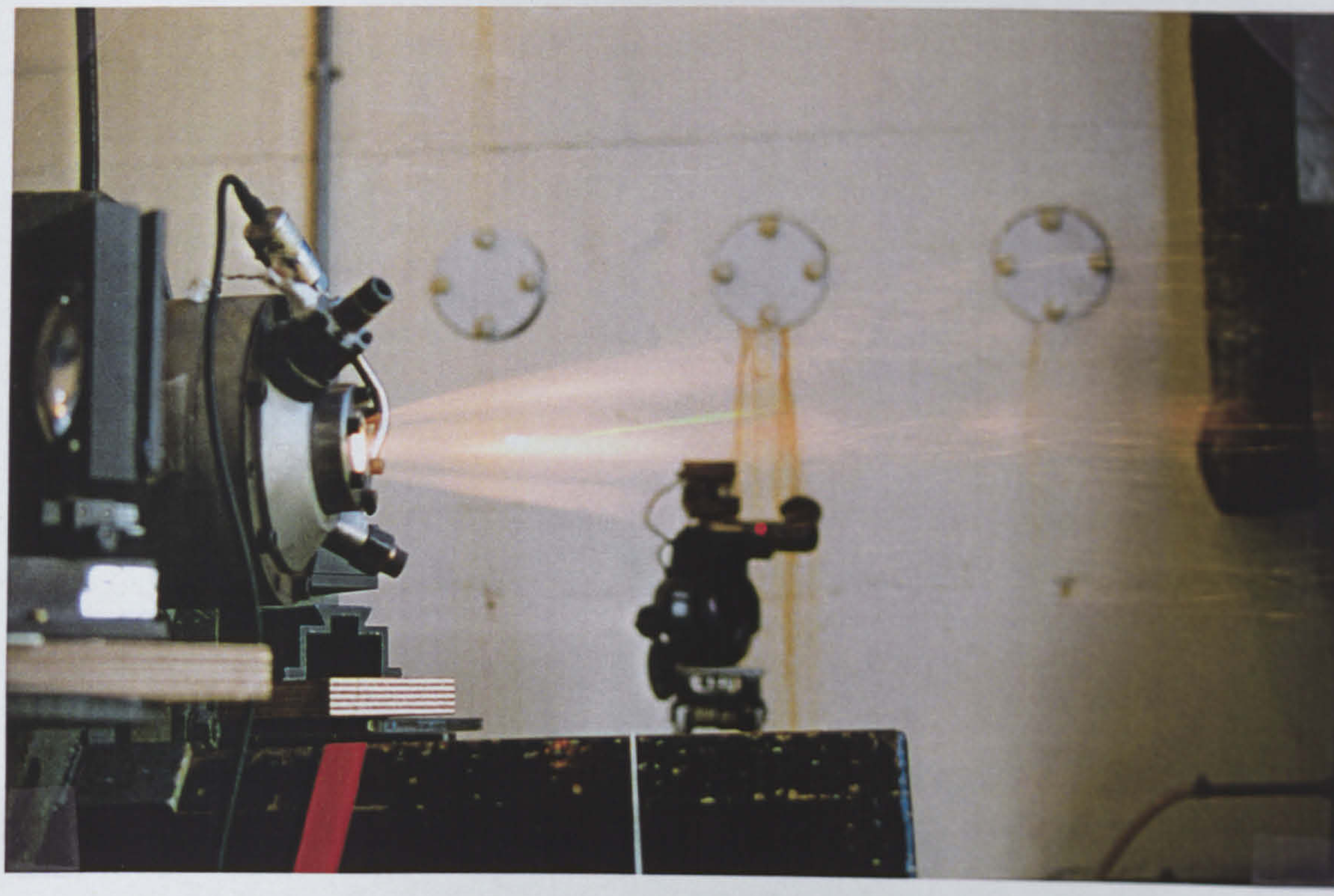


Figure 6.15 Heavyweight motor firing (no seeding)

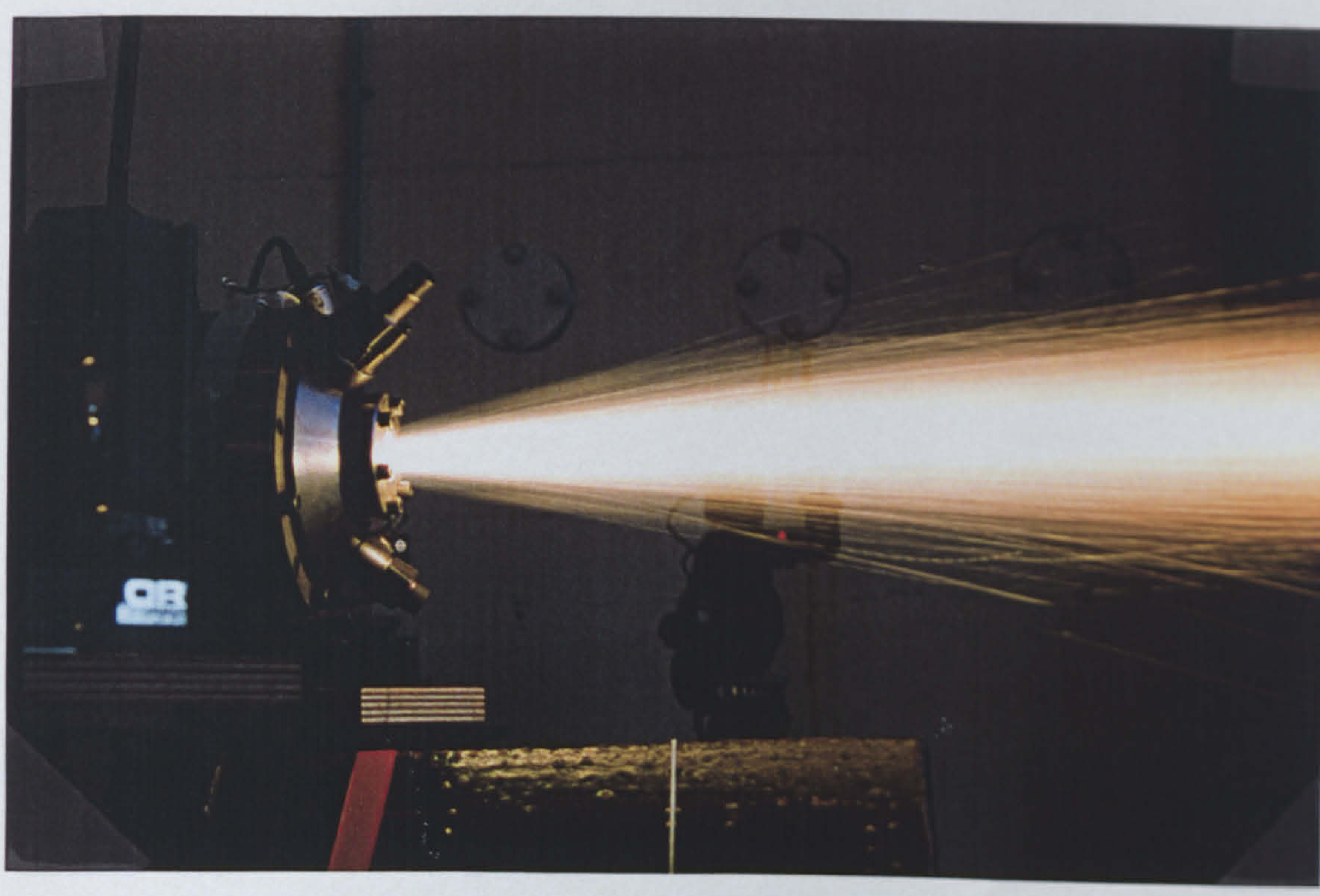


Figure 6.16 Heavyweight motor firing (2% silicon carbide seeding)

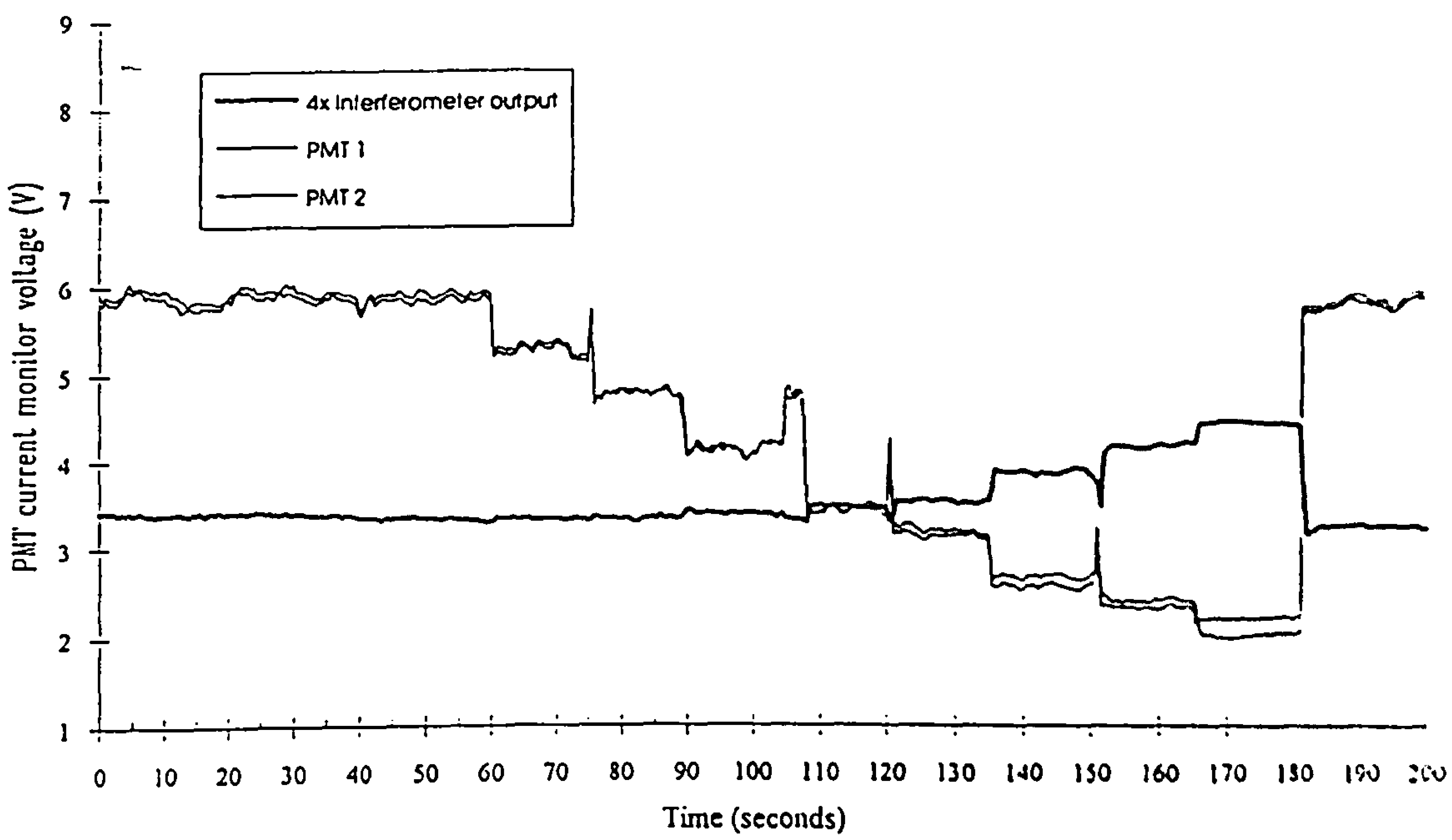


Figure 6.17 Interferometer and PMT outputs for a range of signal light intensities

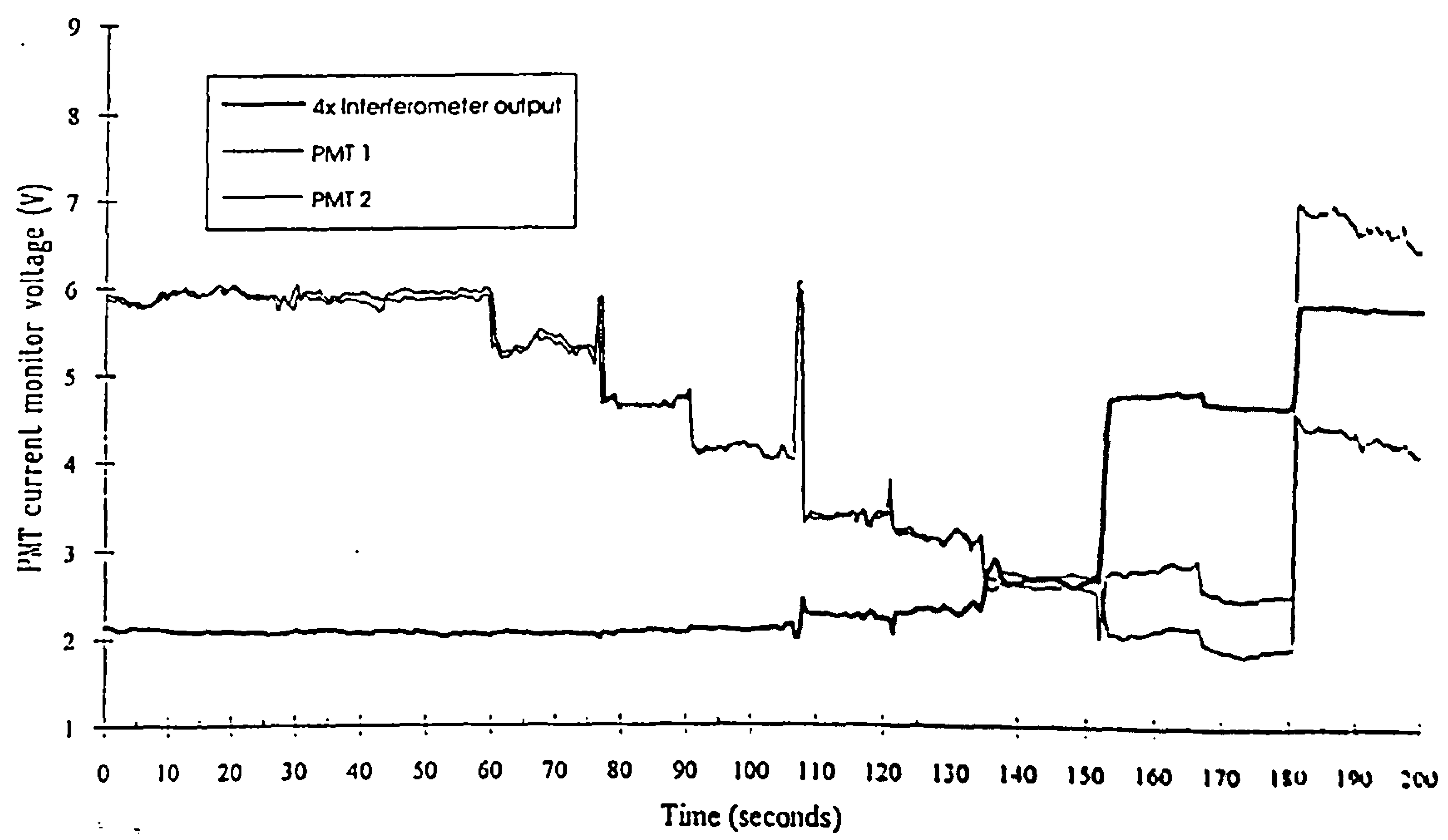


Figure 6.18 Interferometer and PMT outputs with increased background light

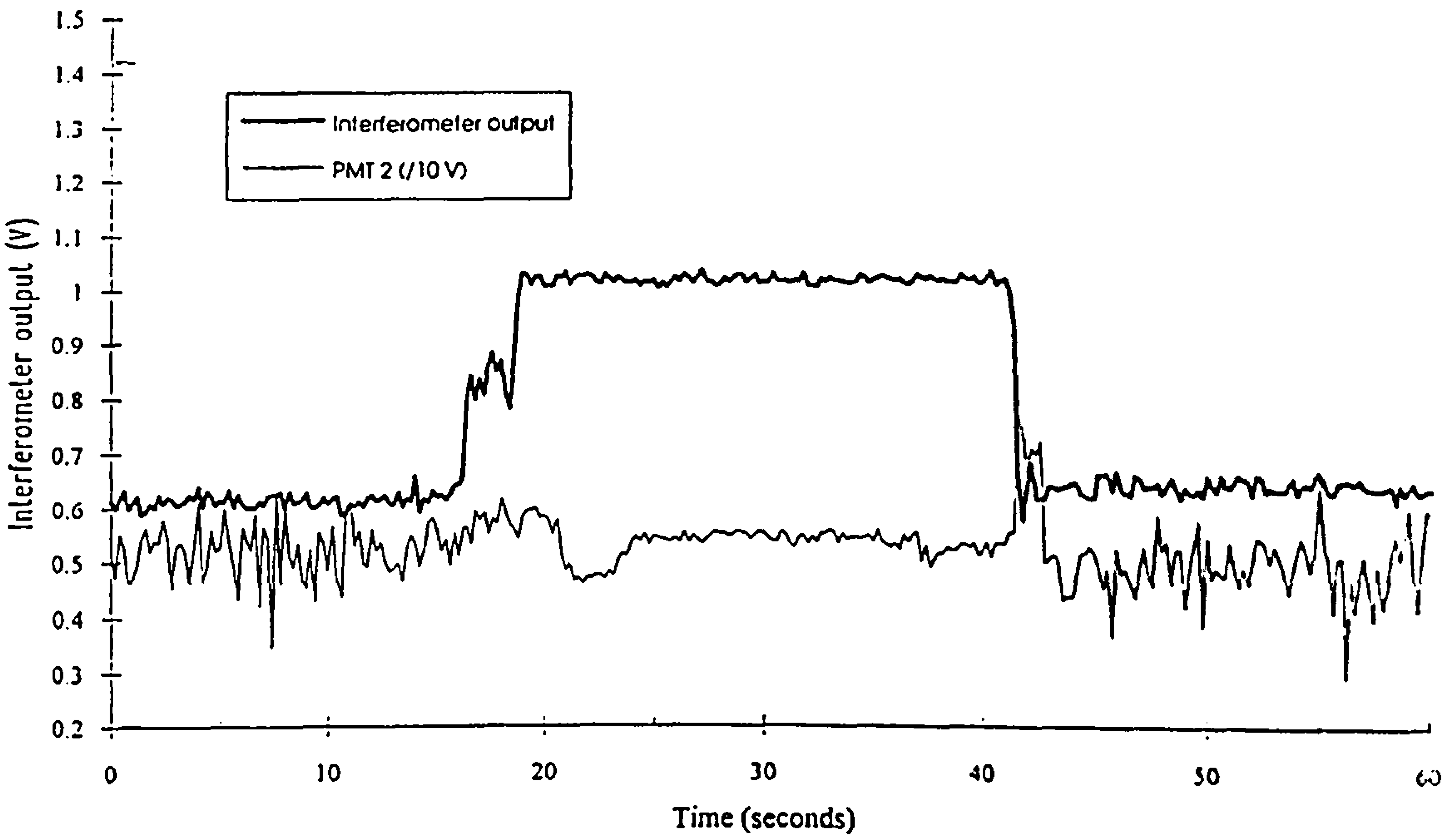


Figure 6.19 Interferometer and PMT outputs for a 198m/s flow

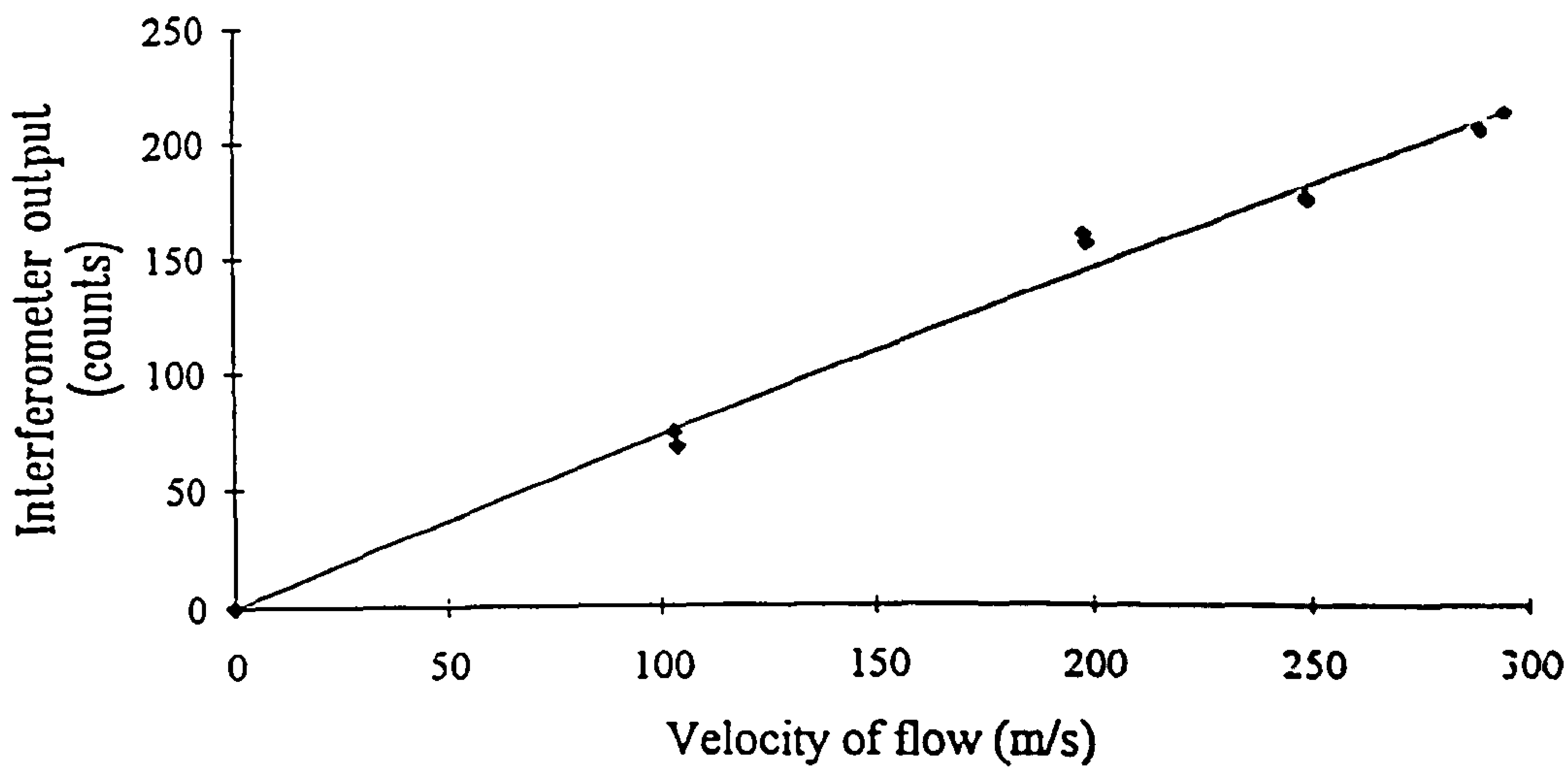


Figure 6.20 Interferometer output against flow velocity measured by Pitot tube

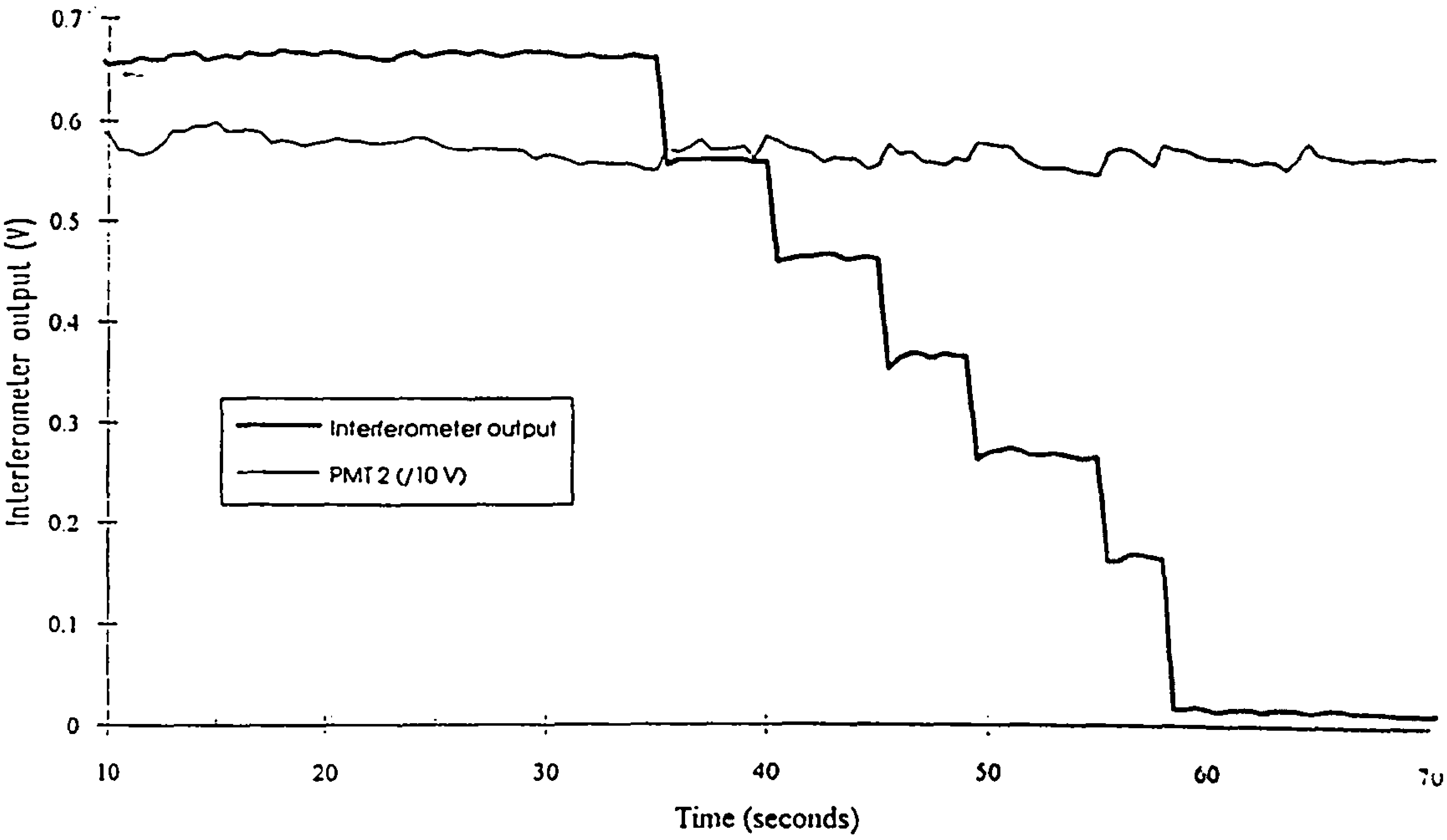


Figure 6.21 Interferometer and PMT outputs during laser mode hops

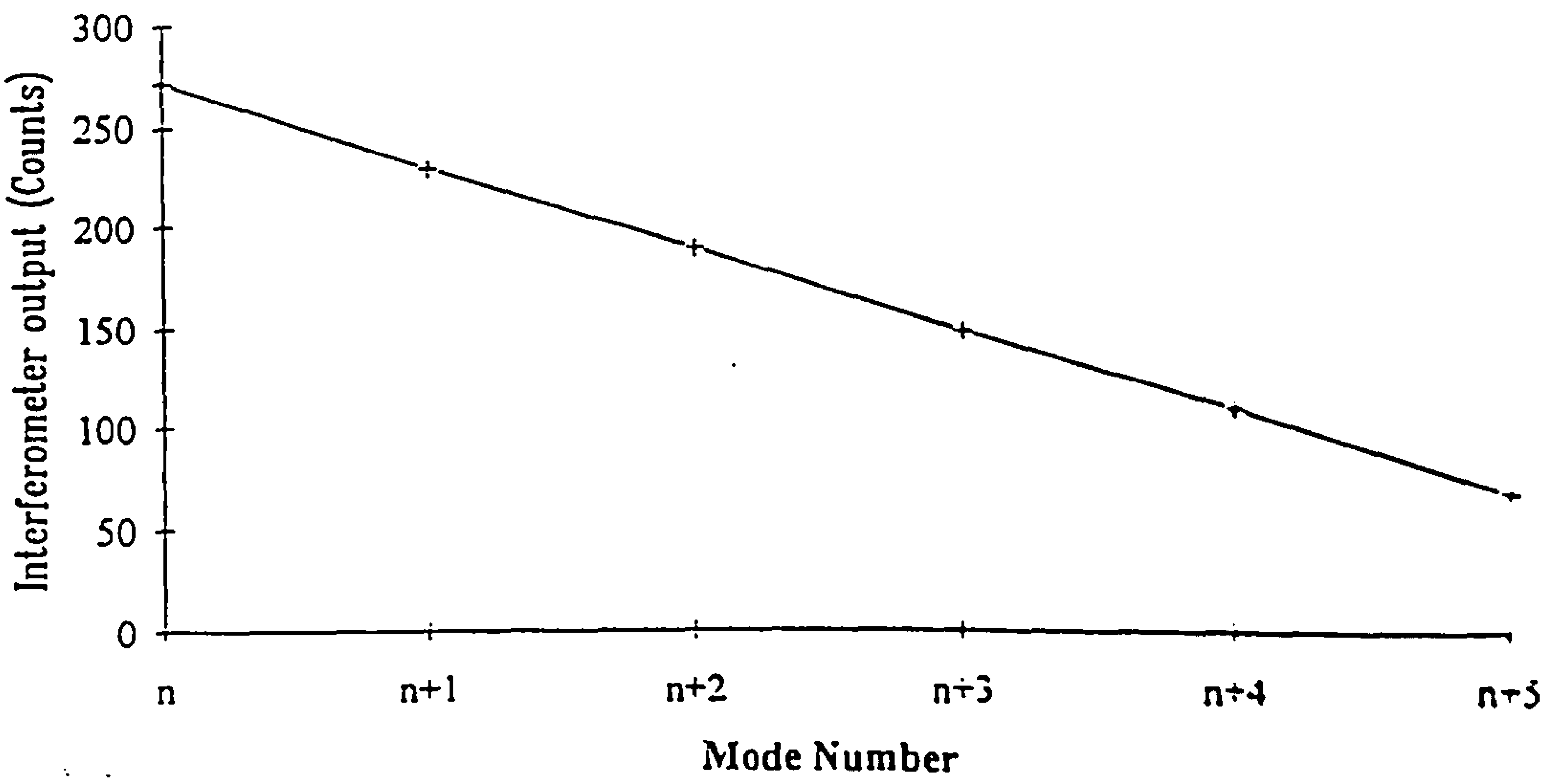


Figure 6.22 Mean interferometer output as a funtion of laser mode hops

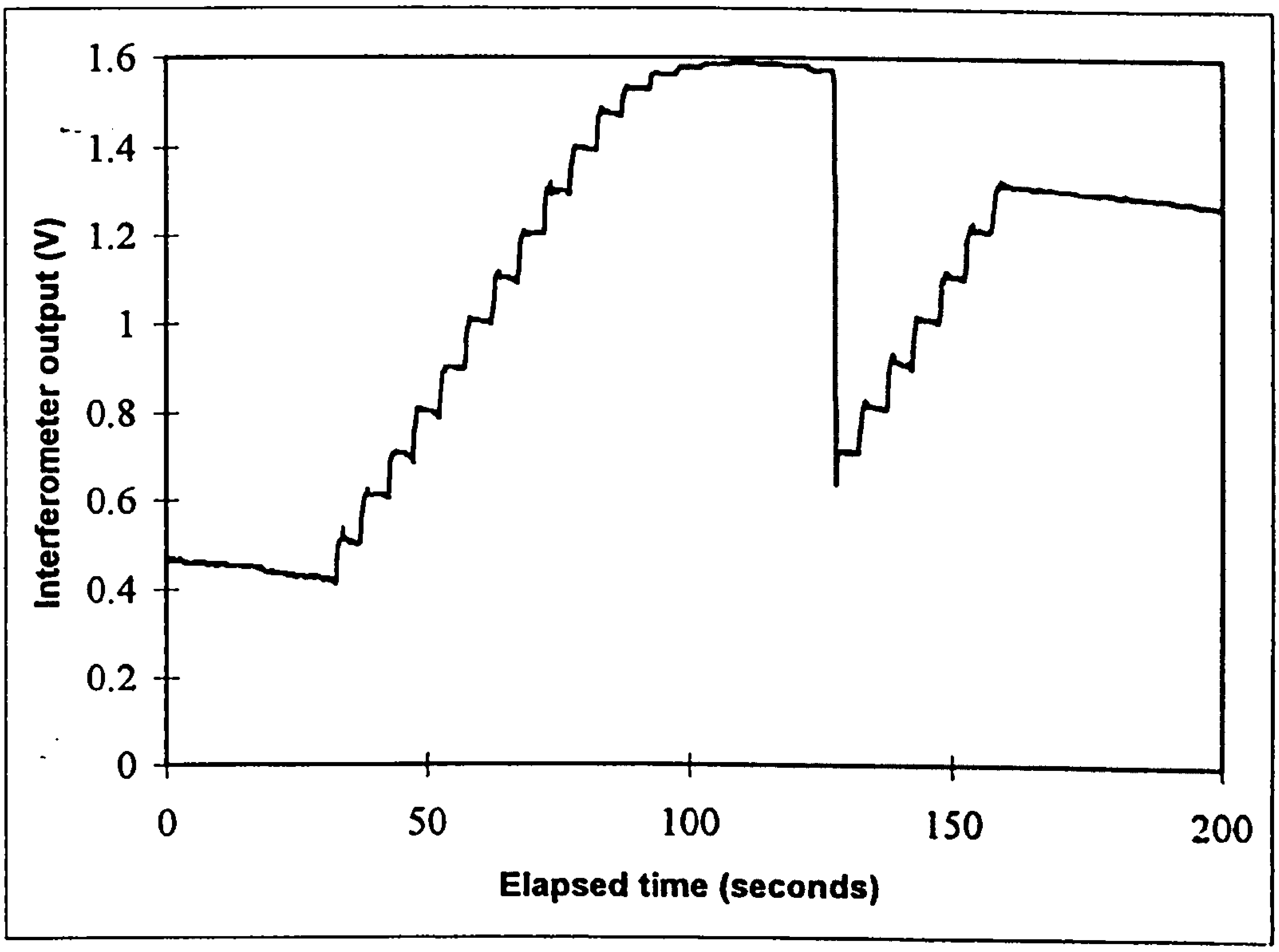


Figure 6.23 Interferometer calibration number 1

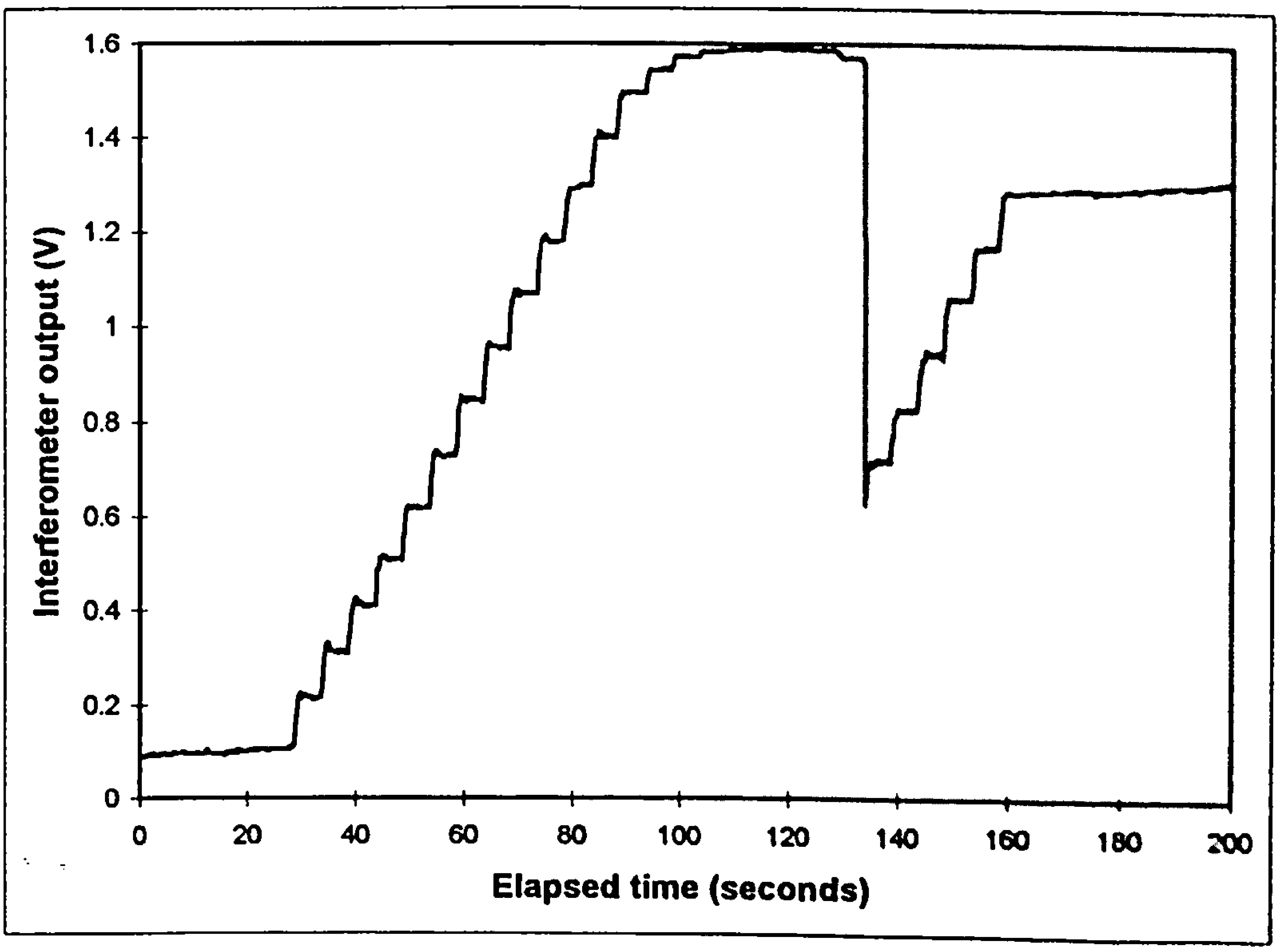


Figure 6.24 Interferometer calibration number 2

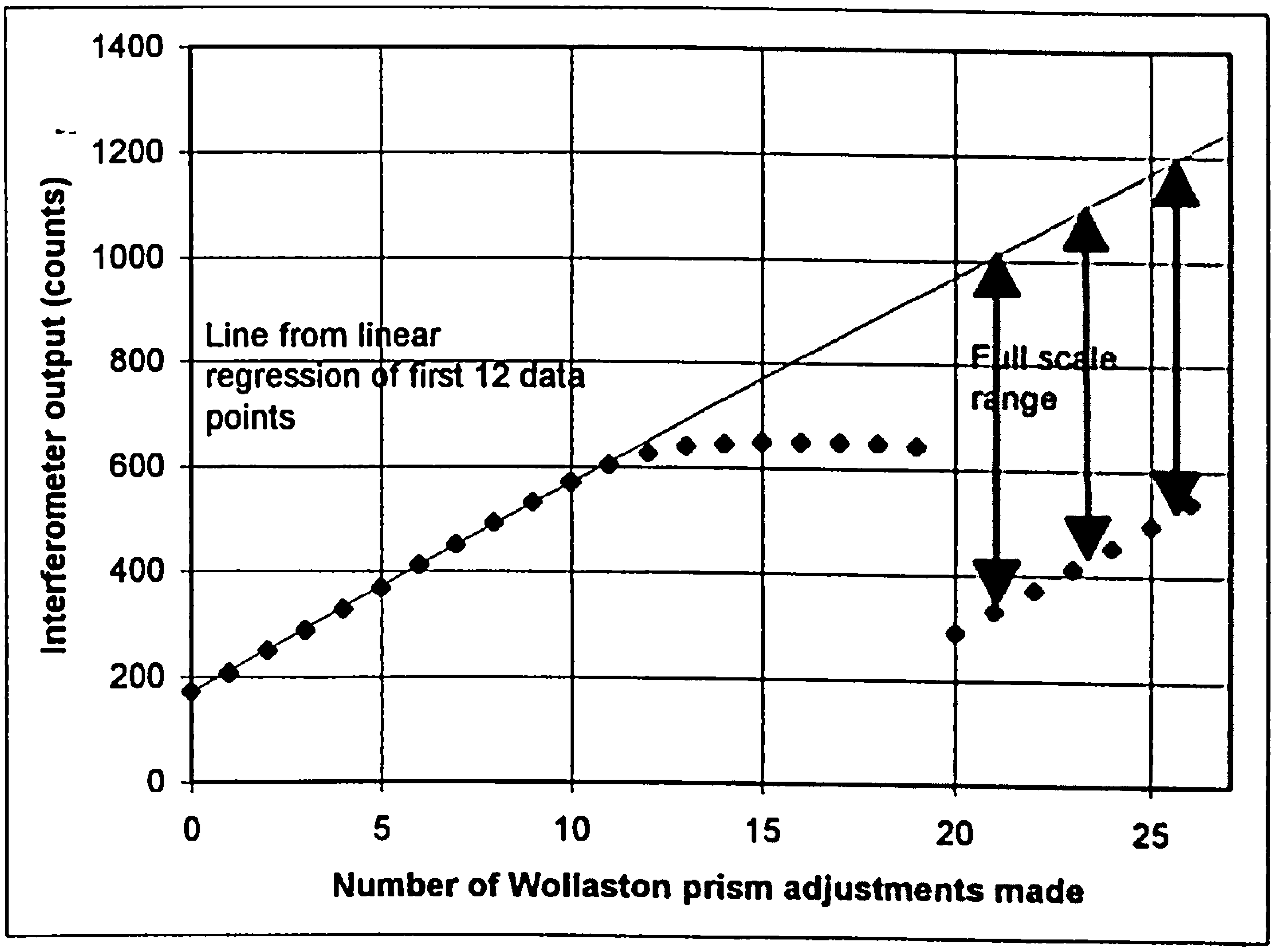


Figure 6.25 Interferometer output against prism adjustments for Calibration 1

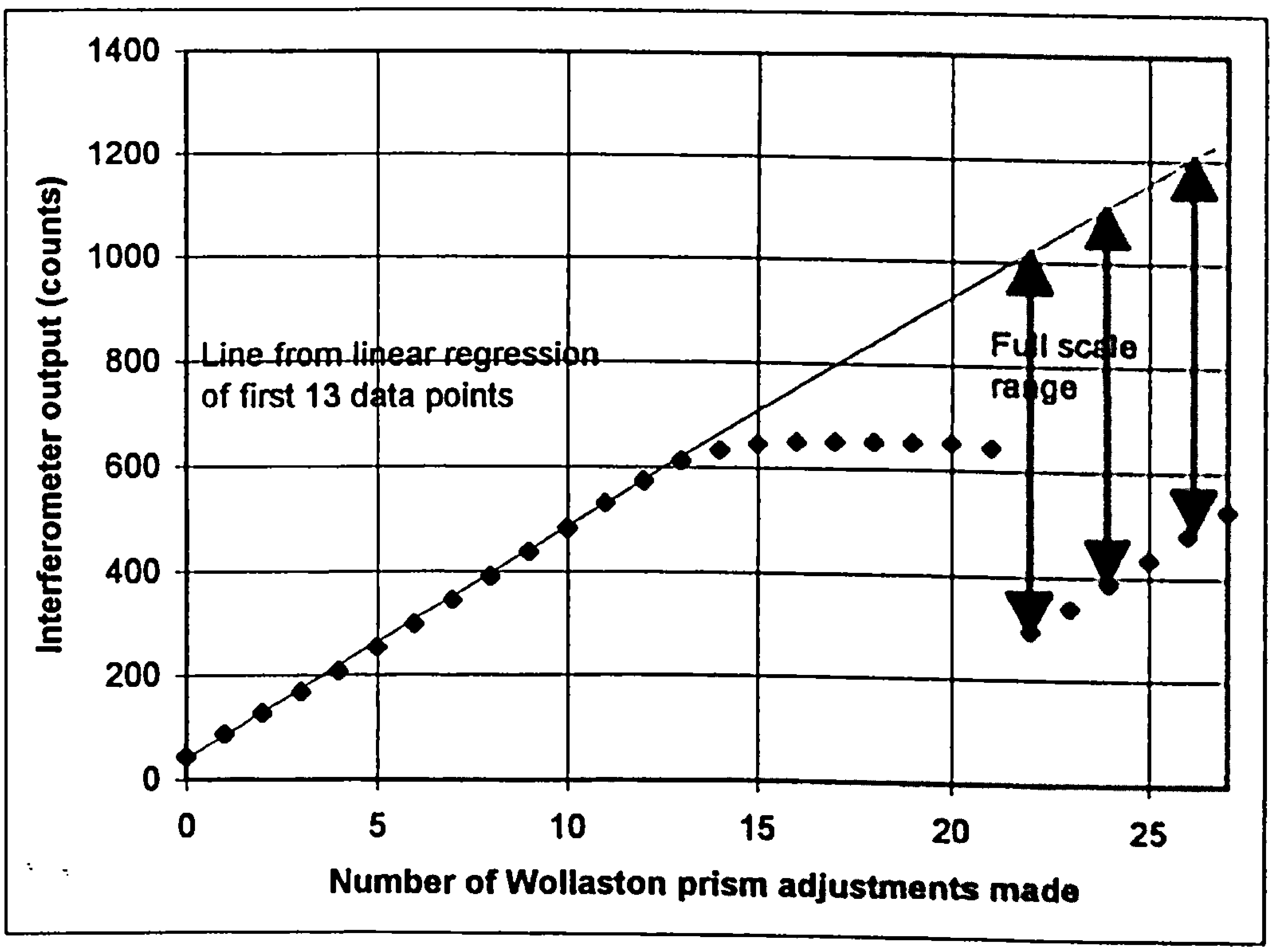


Figure 6.26 Interferometer output against prism adjustments for Calibration 2

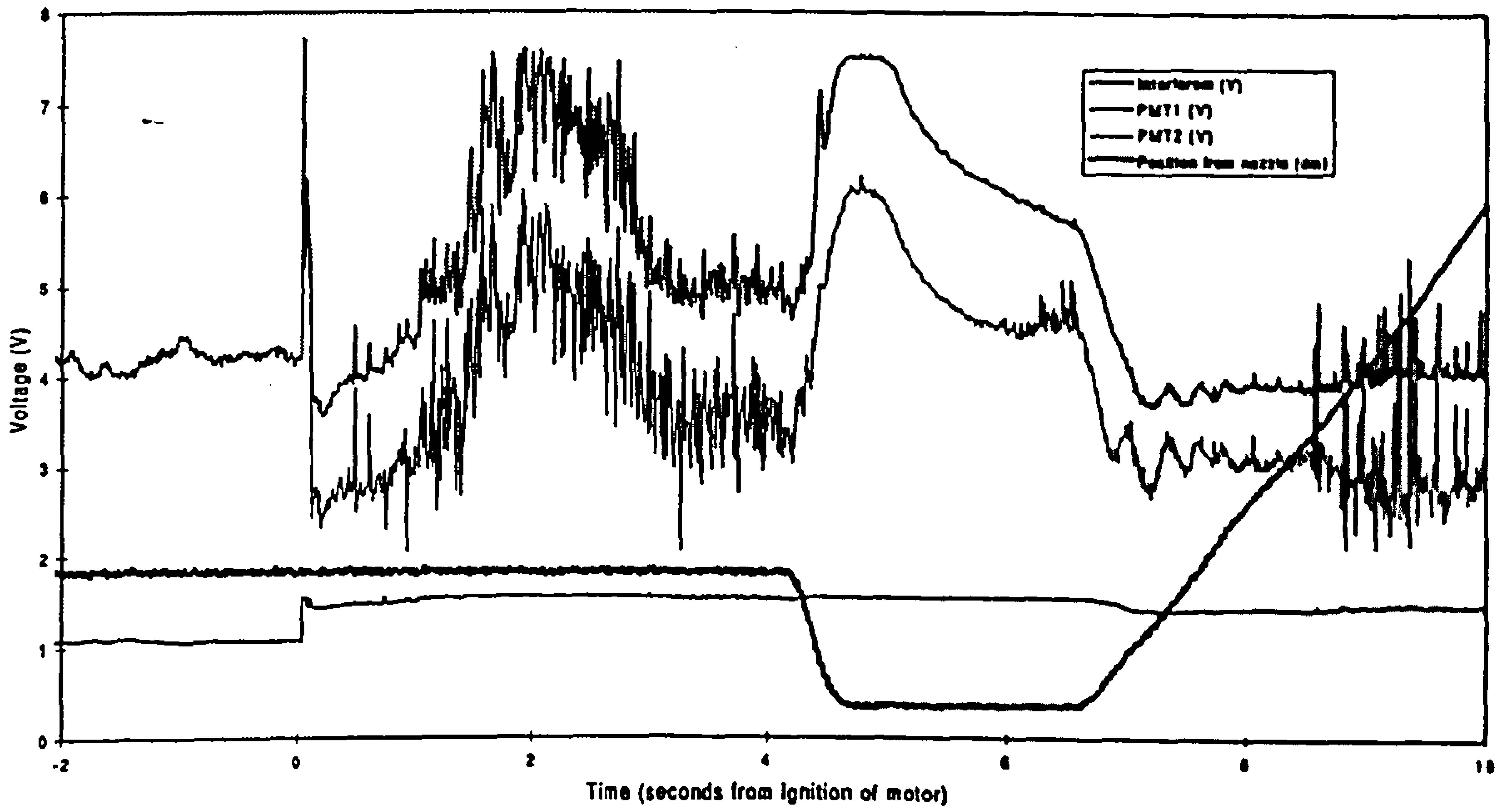


Figure 6.27 Data collected from Firing A2 (CDB 2)

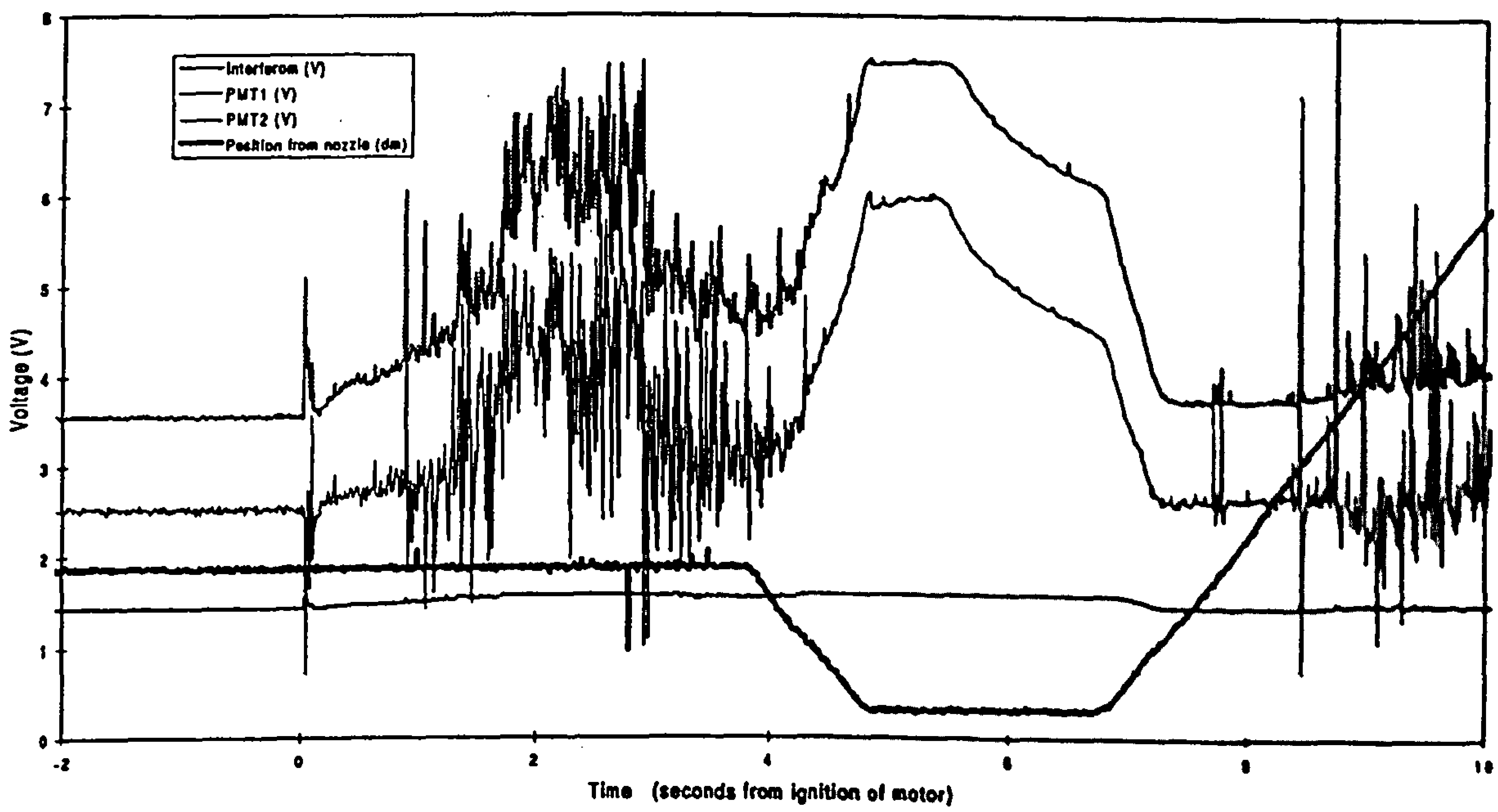


Figure 6.28 Data collected from Firing A3 (CDB 3)

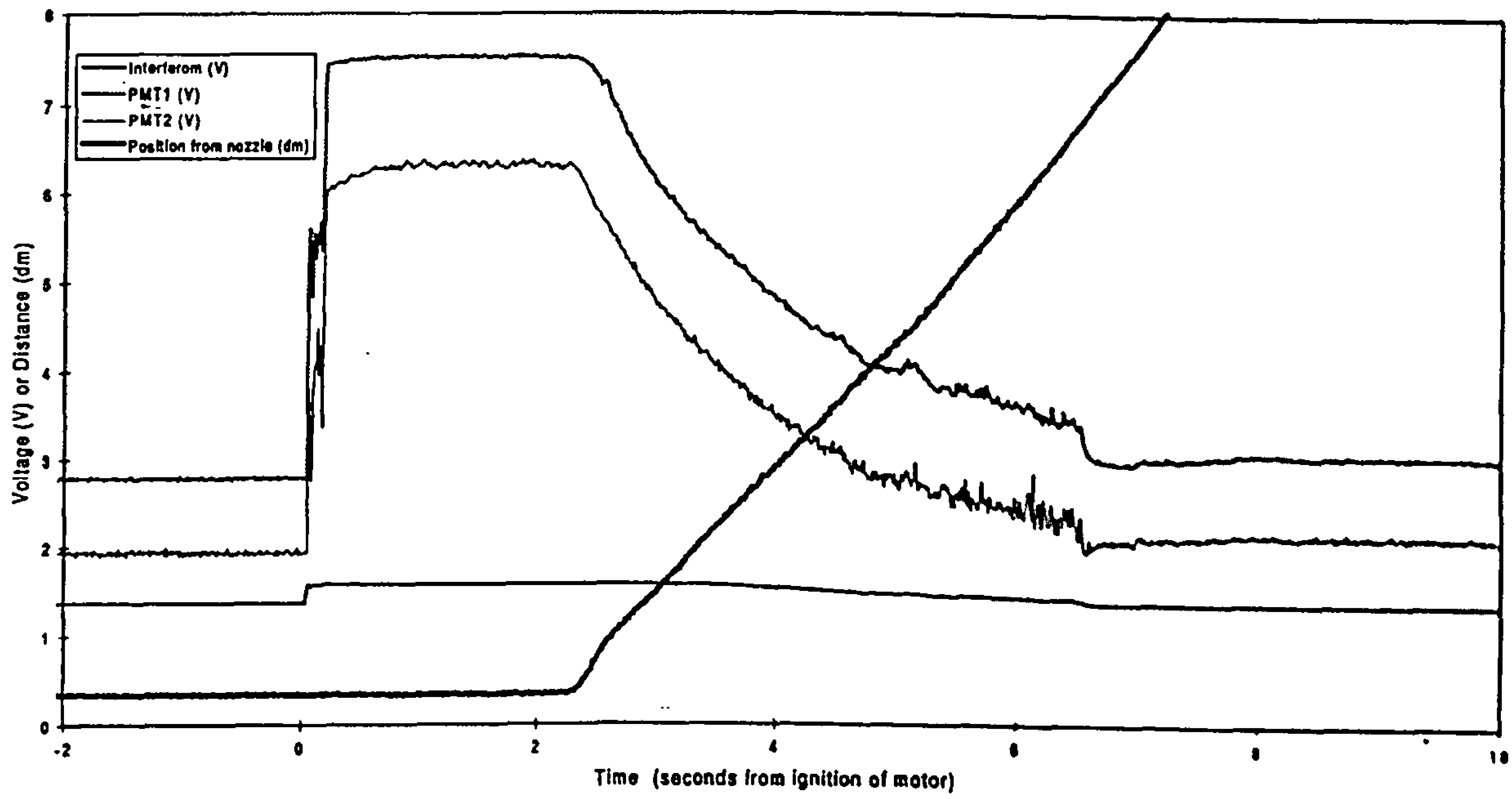


Figure 6.29 Data collected from Firing A4 (Heavyweight 1)

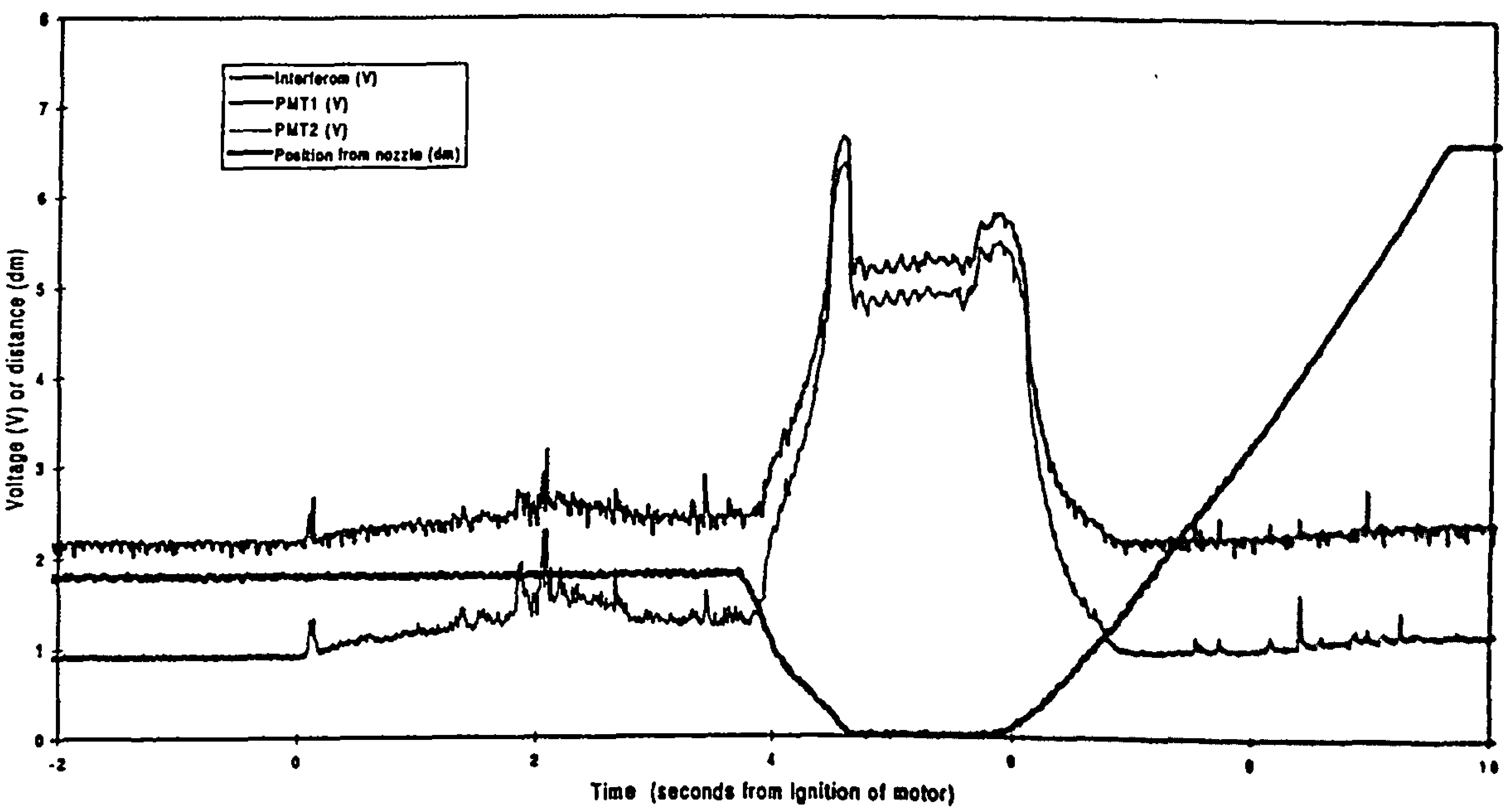


Figure 6.30 Data collected from Firing A5 (CDB 4)

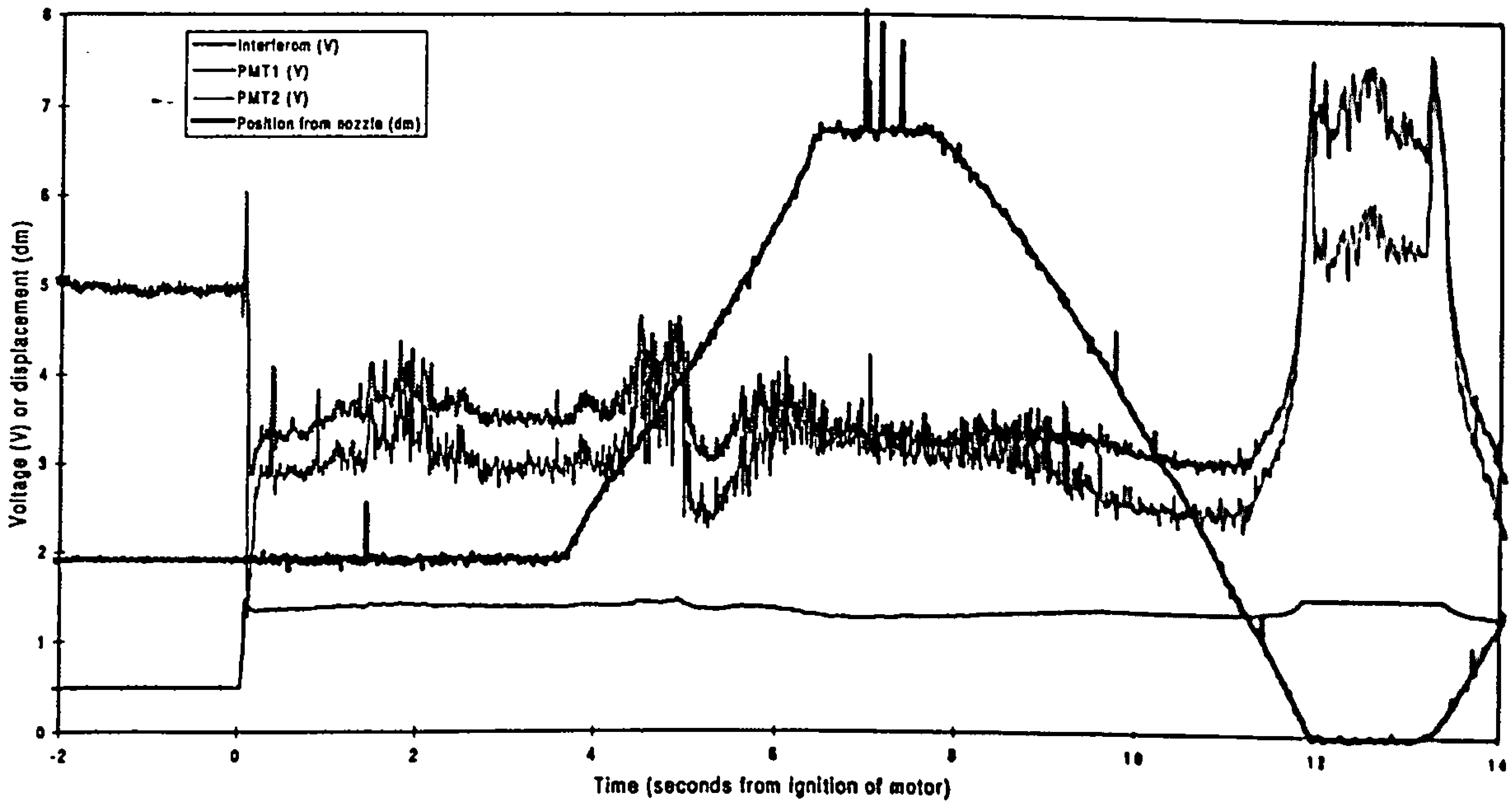


Figure 6.31 Data collected from Firing A7 (CDB 6)

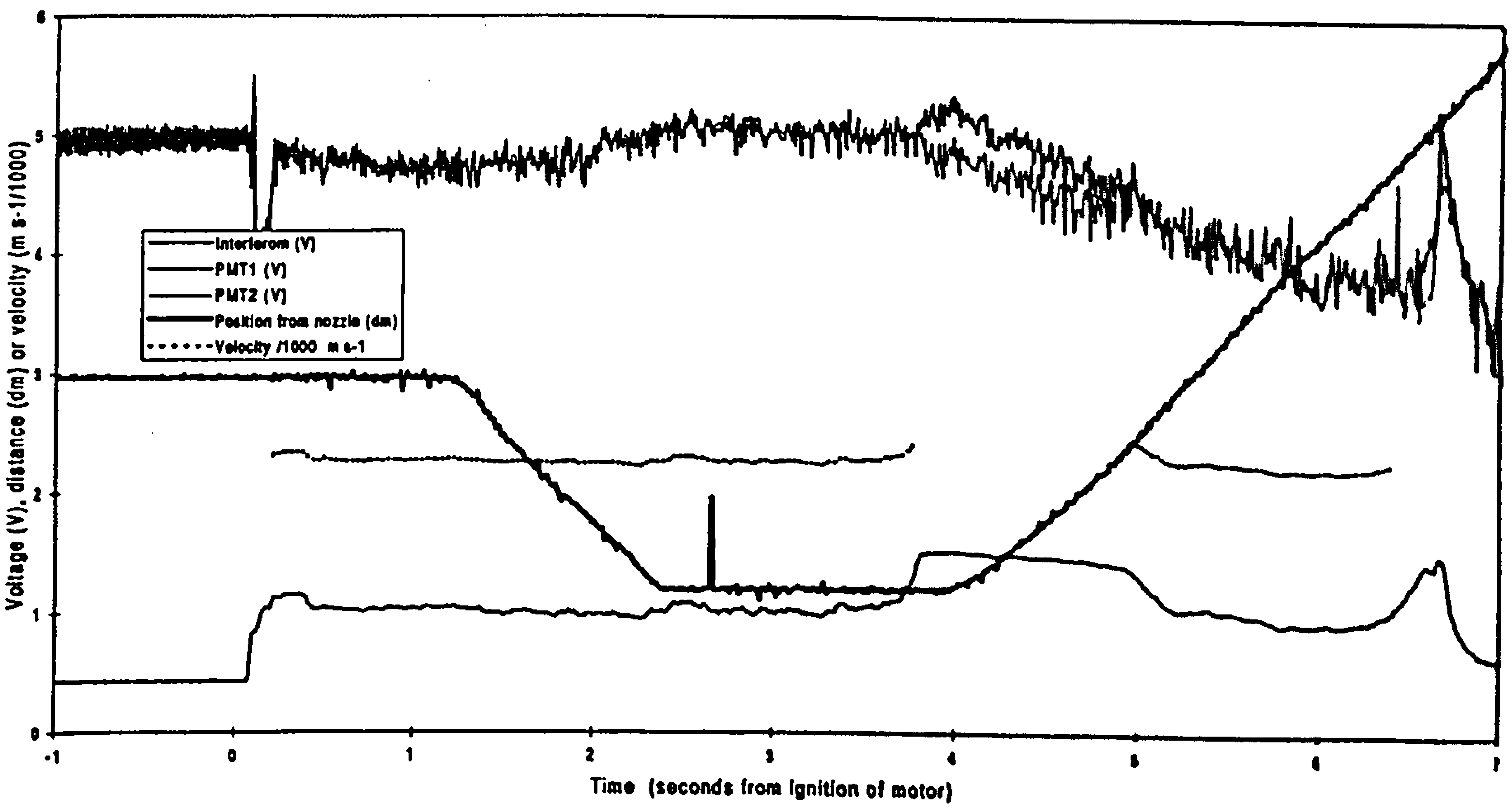


Figure 6.32 Data collected from Firing A8 (Heavyweight 2)

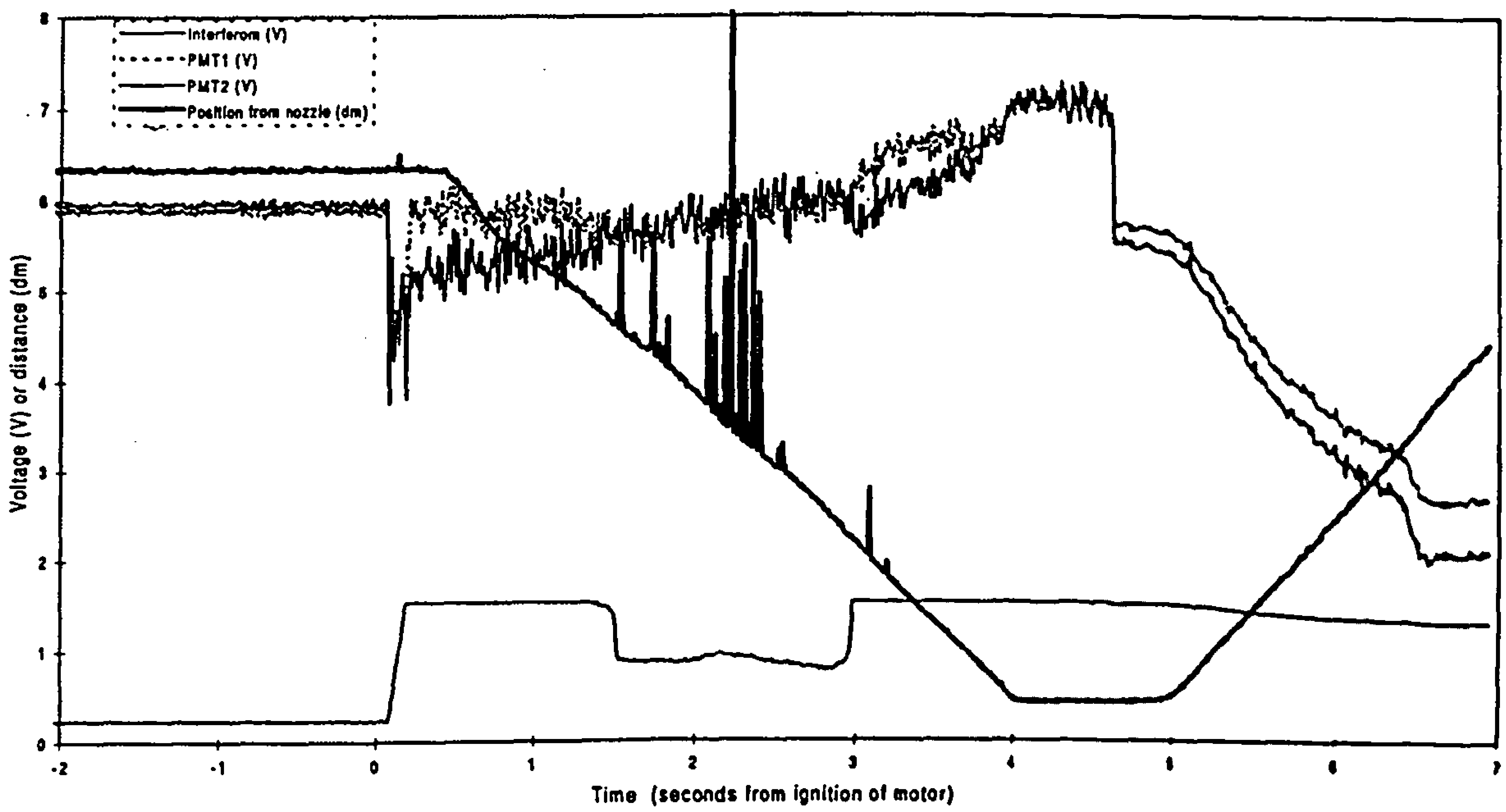


Figure 6.33 Data collected from Firing A9 (Heavyweight 3)

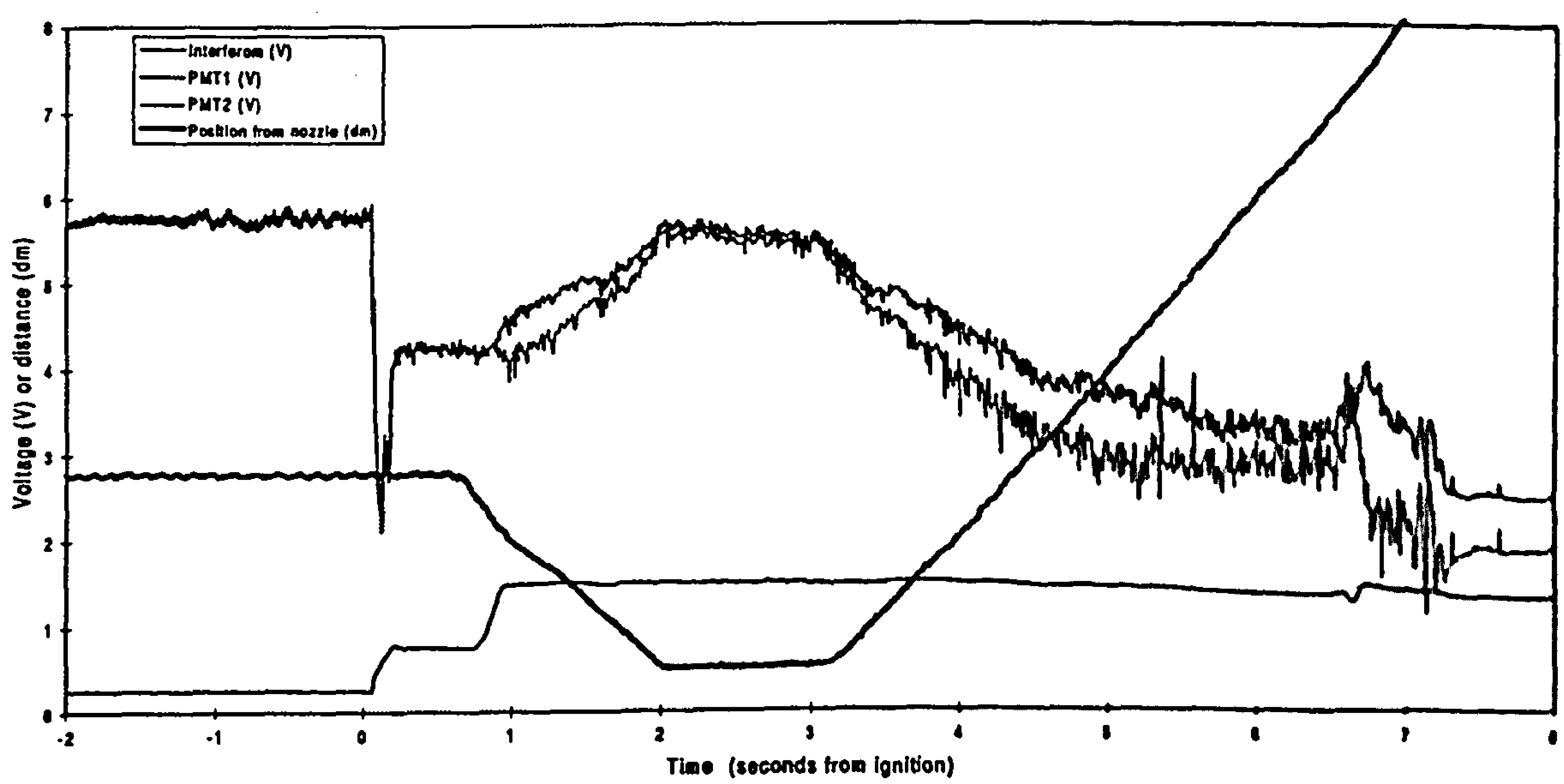


Figure 6.34 Data collected from Firing A10 (Heavyweight 4)

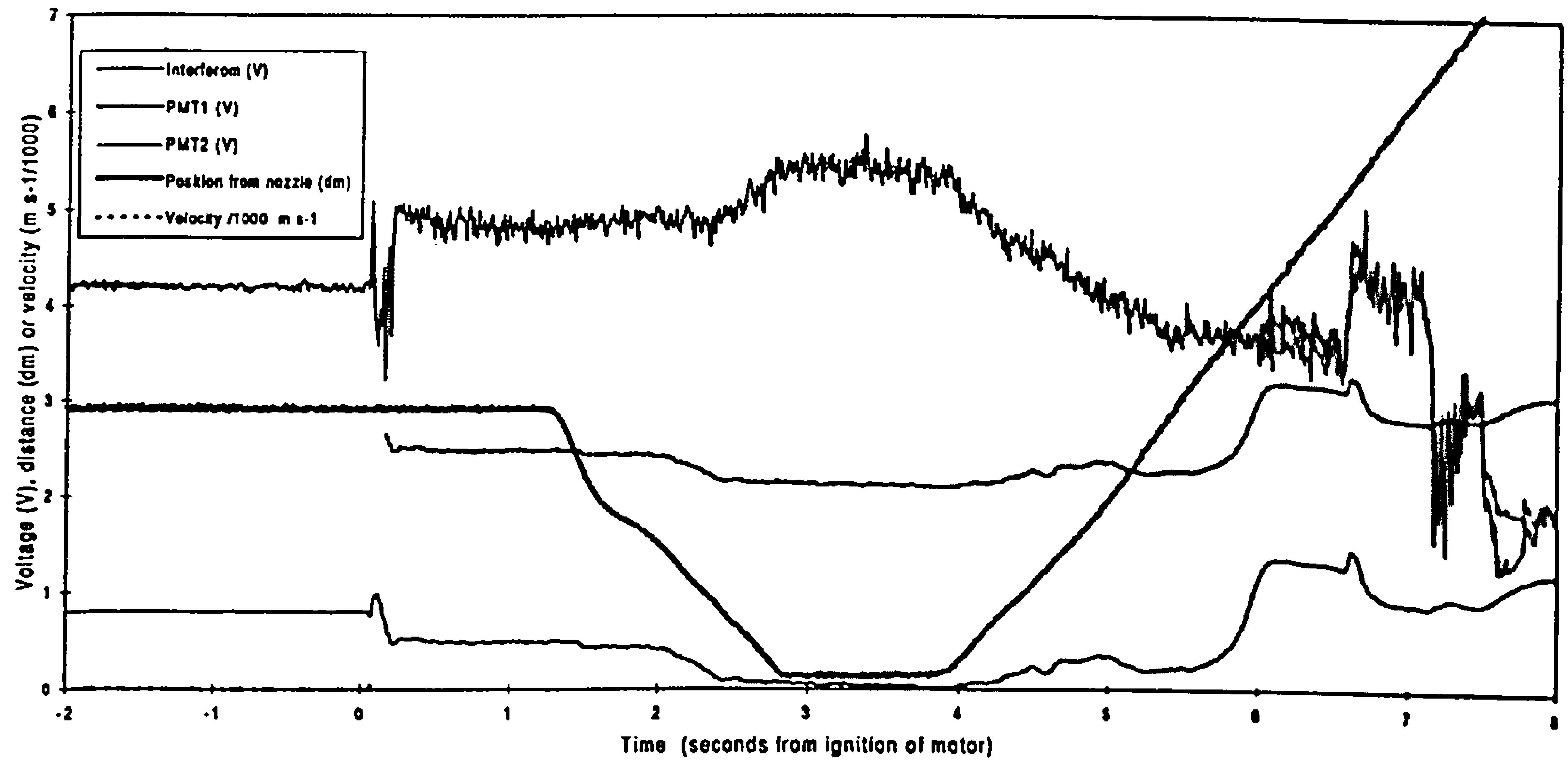


Figure 6.35 Data collected from Firing A11 (Heavyweight 5)

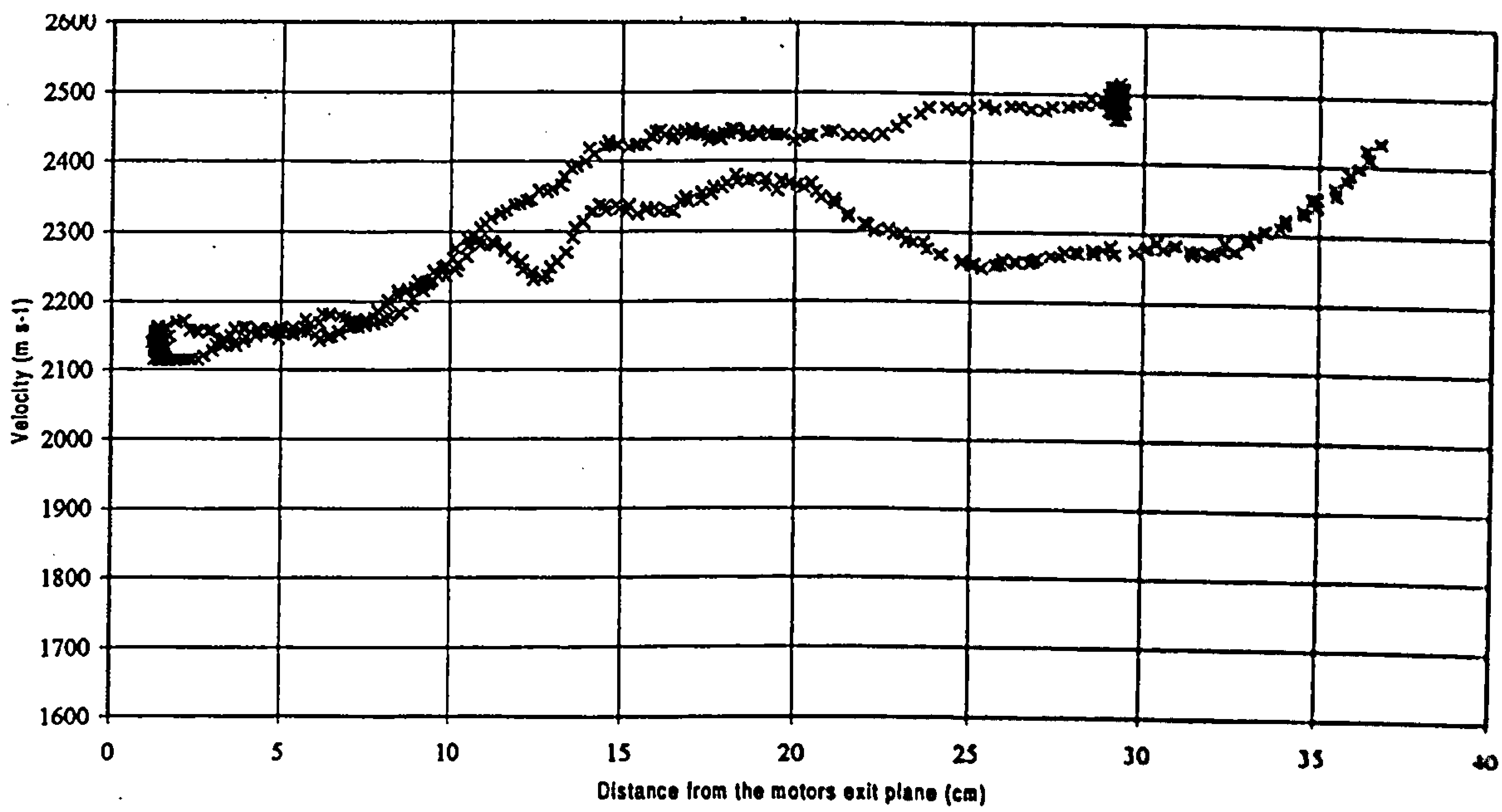


Figure 6.36 Measured velocity profile for Firing 11 (Heavyweight 5)

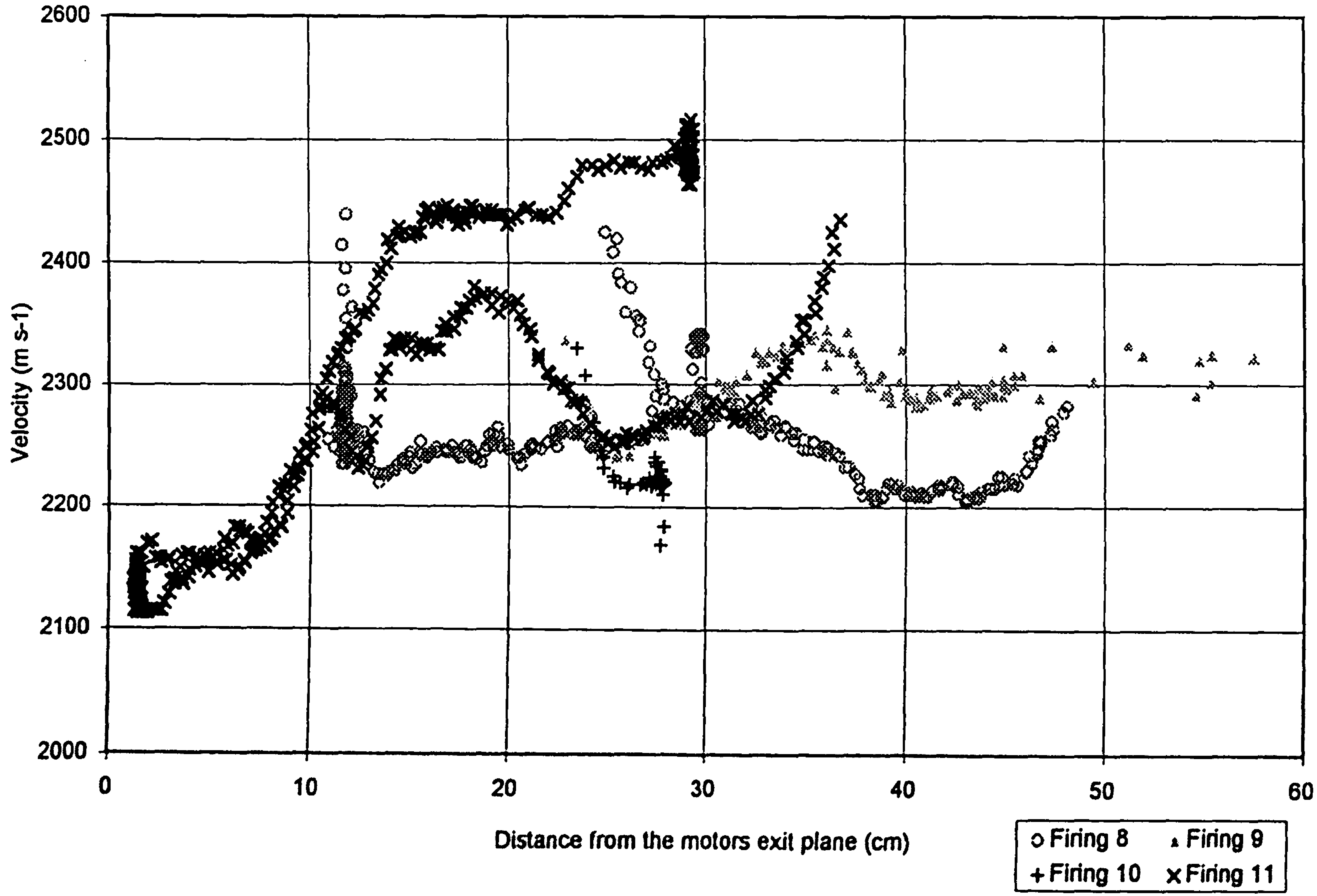


Figure 6.37 Measured velocity profiles for all Heavyweight motors

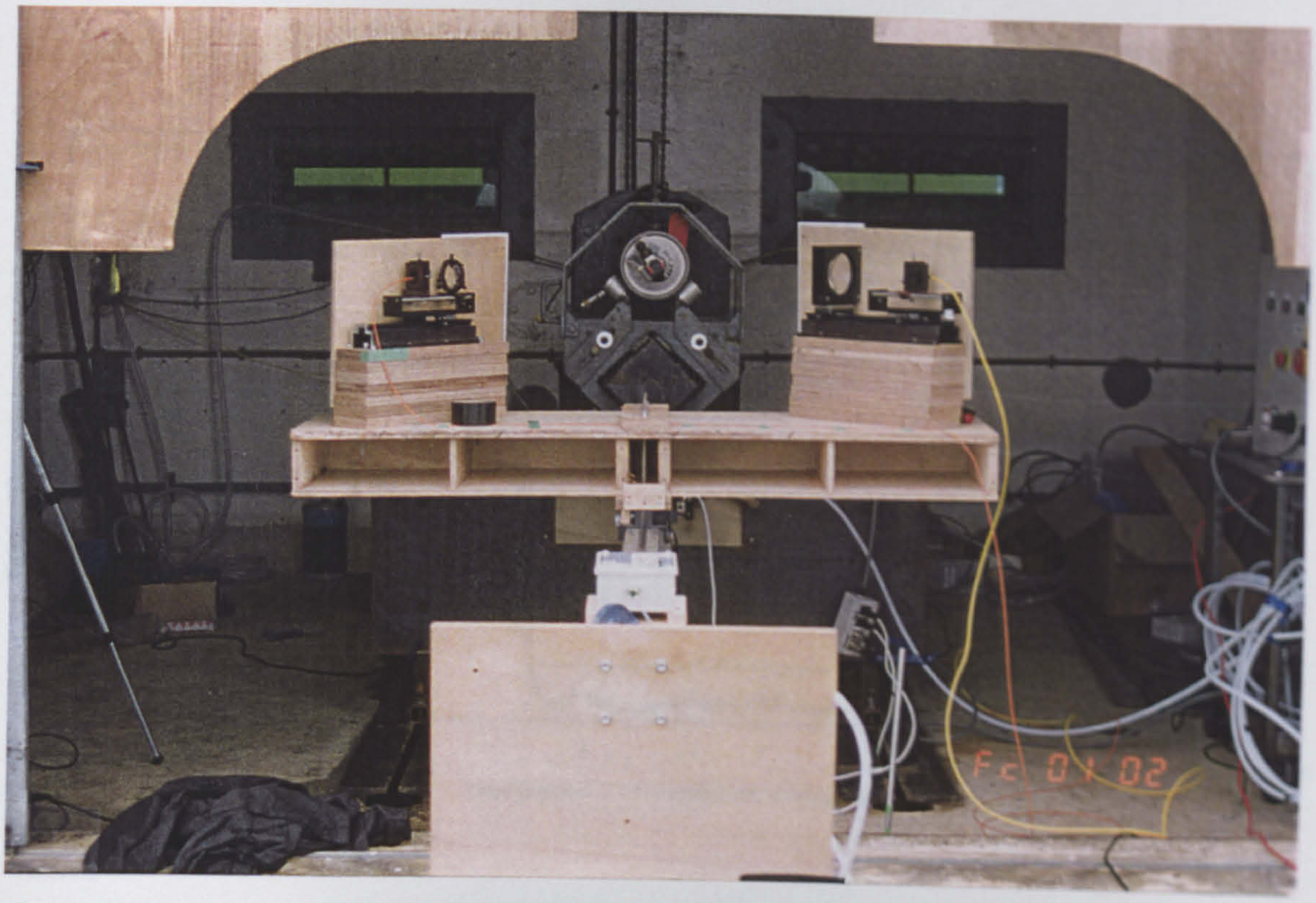


Figure 6.38 Traversing mechanism used during the velocity profile trial

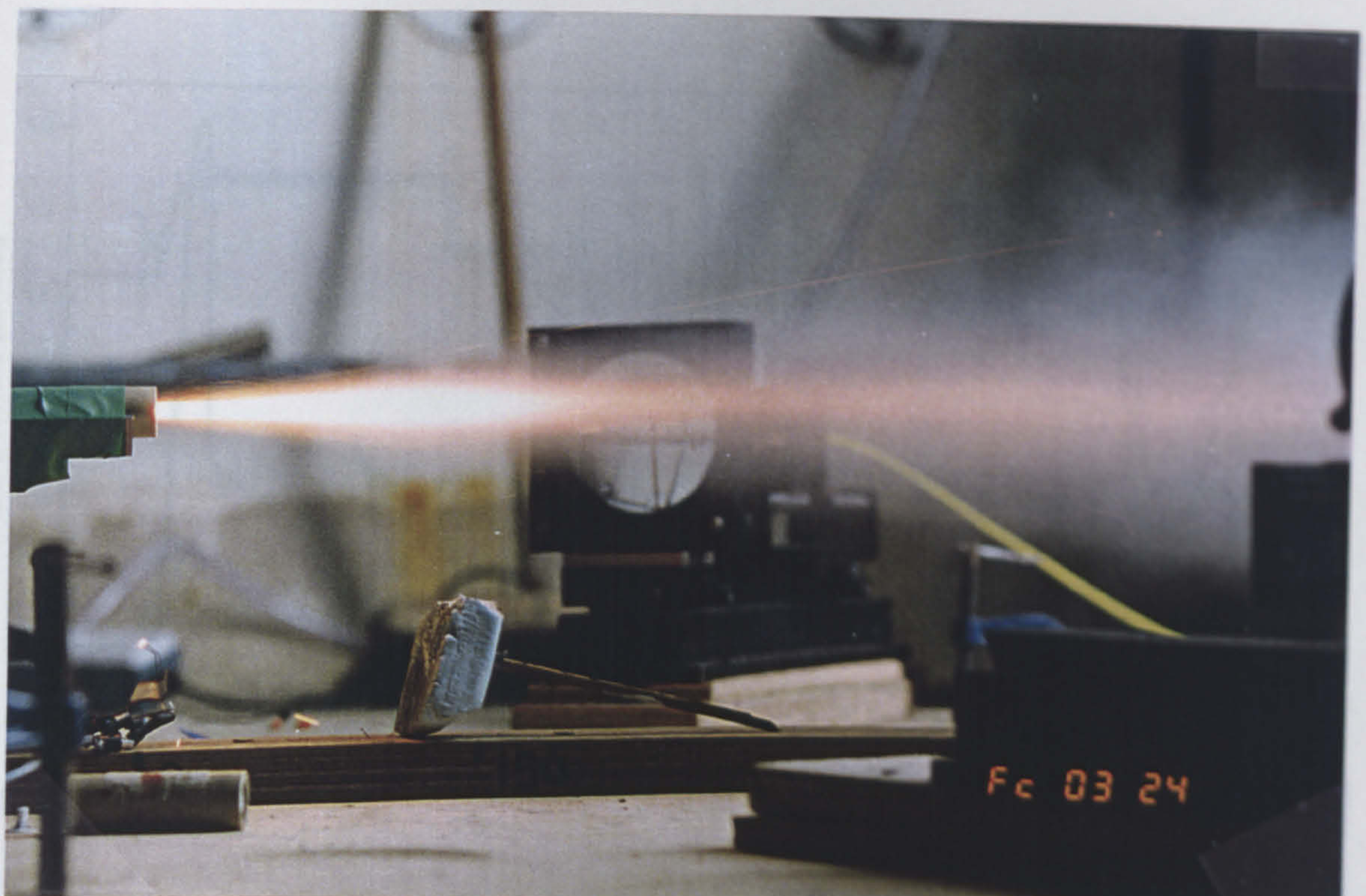


Figure 6.39 Firing of a Mini motor

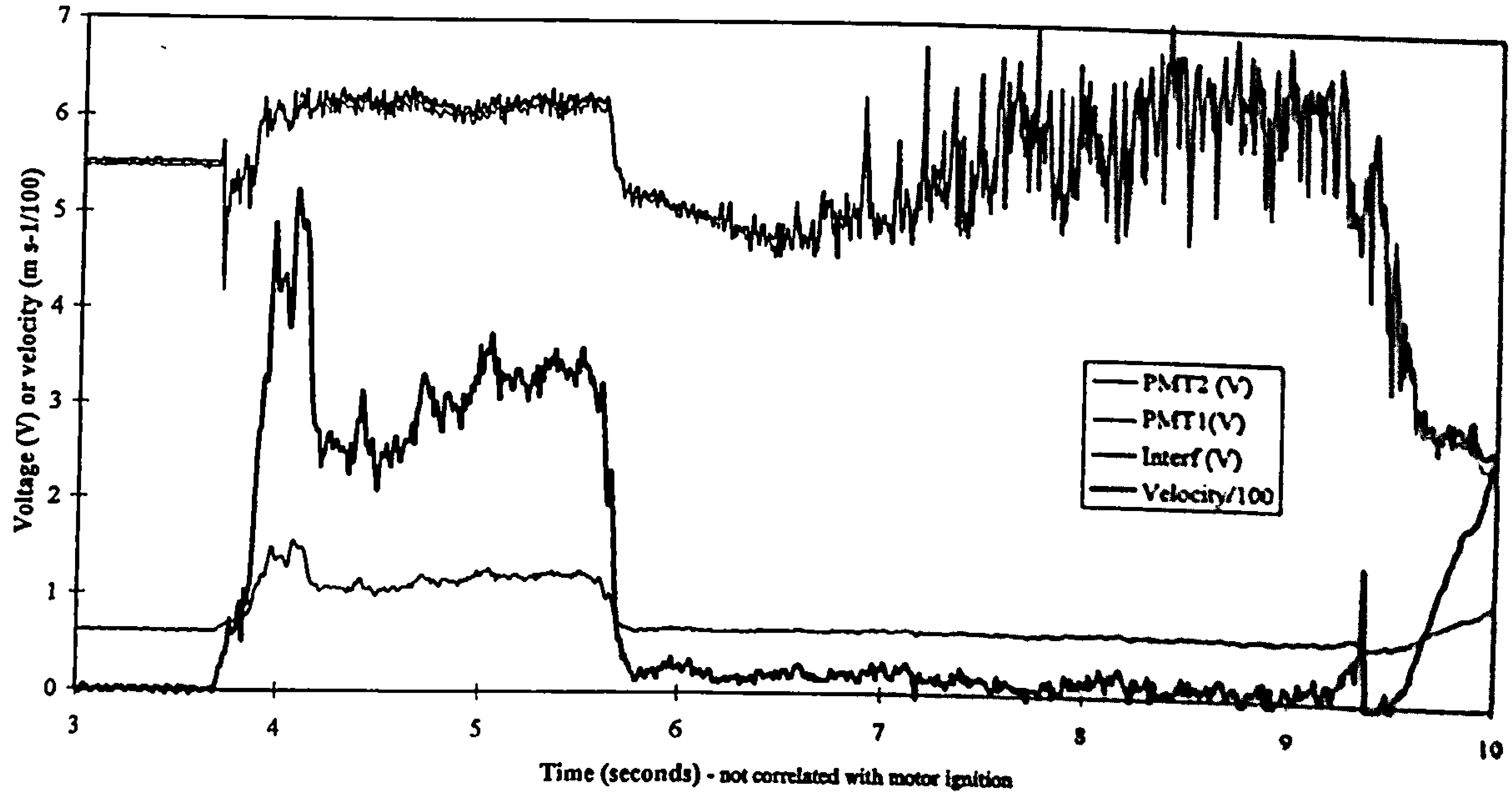


Figure 6.40 Interferometer and PMT outputs for Mini motor Firing M3 (D type, 45mm)

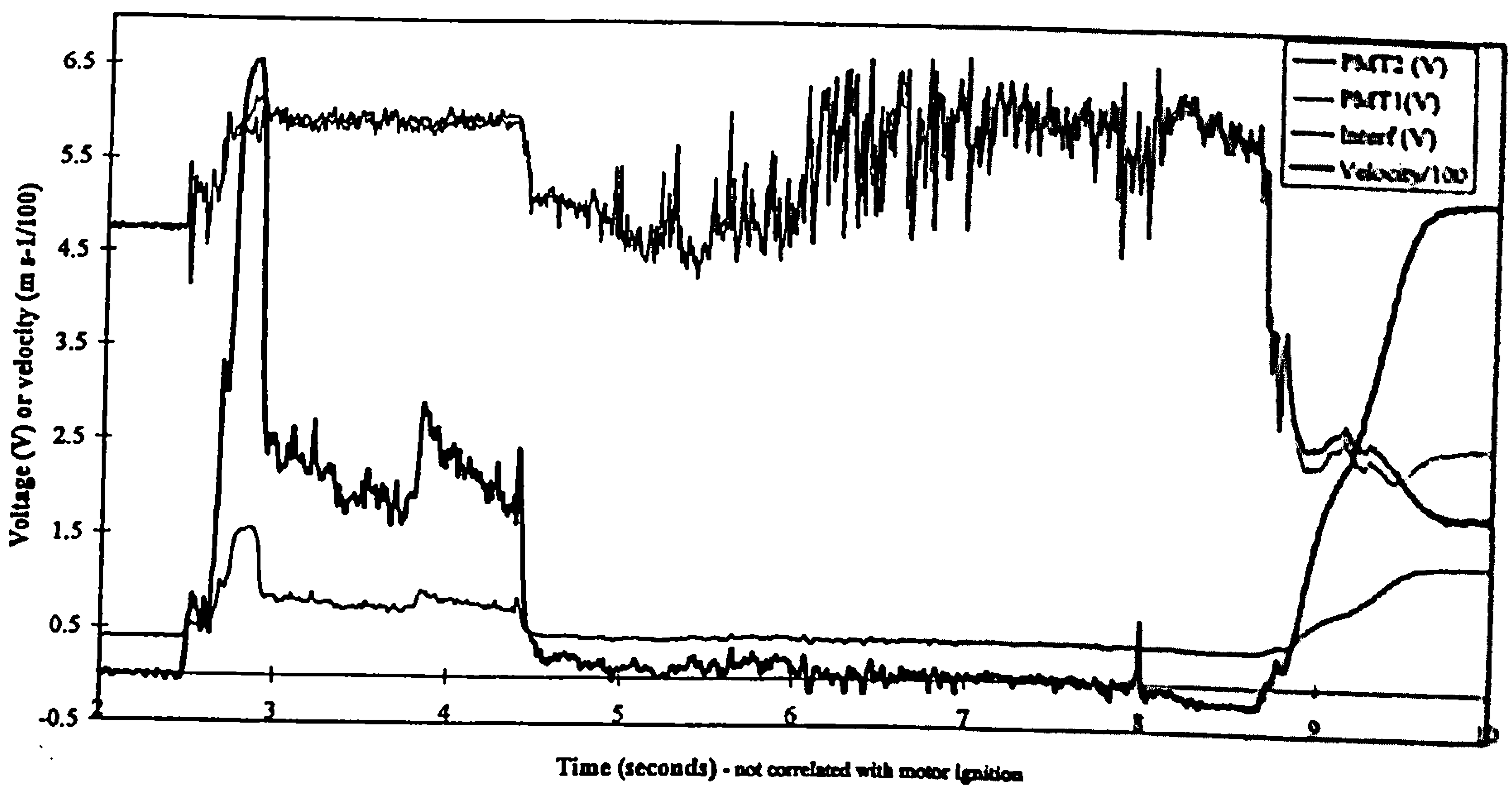


Figure 6.41 Interferometer and PMT outputs for Mini motor Firing M4 (D type, 45mm)

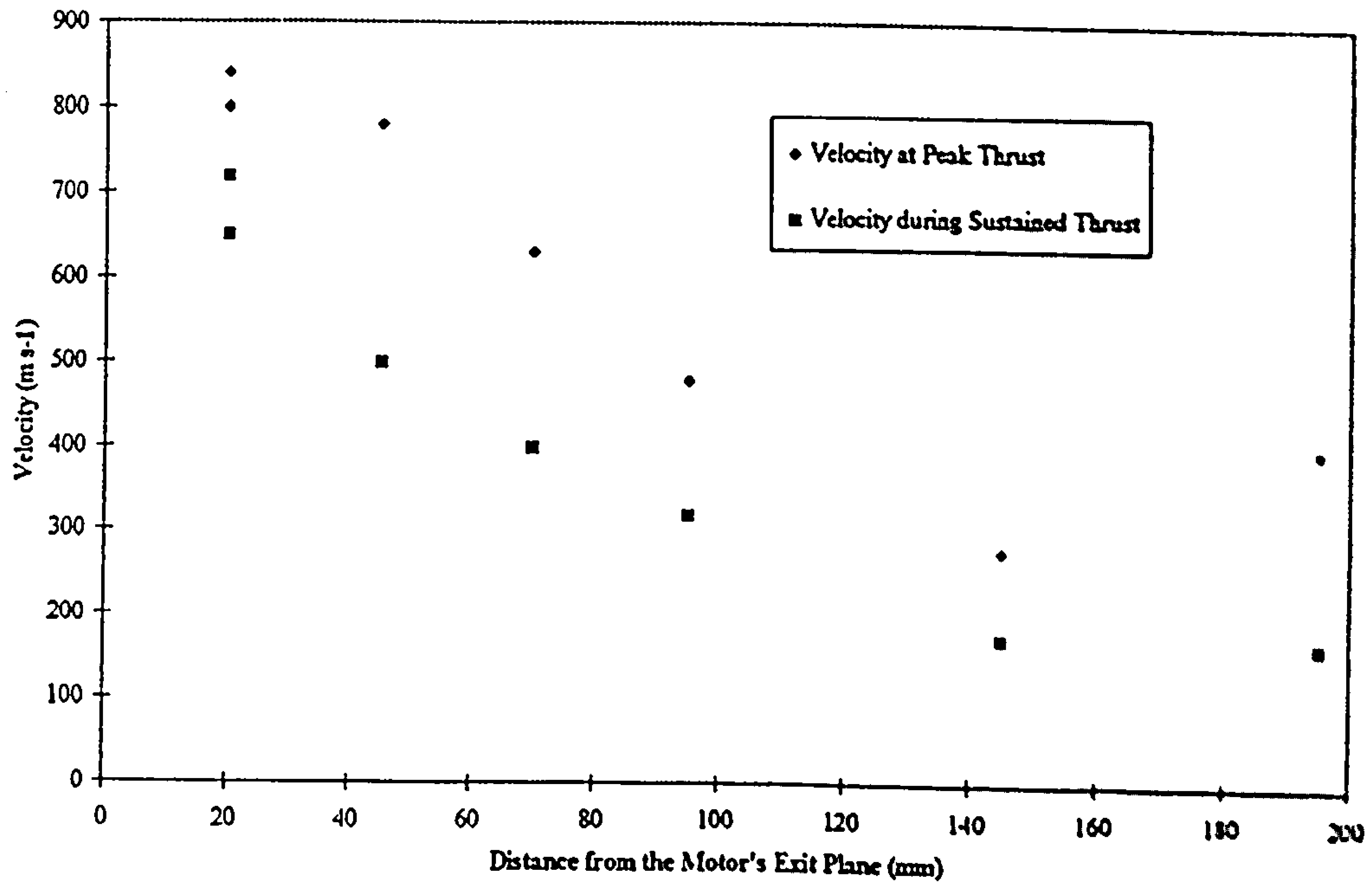


Figure 6.42 Mini motor plume particle velocity map

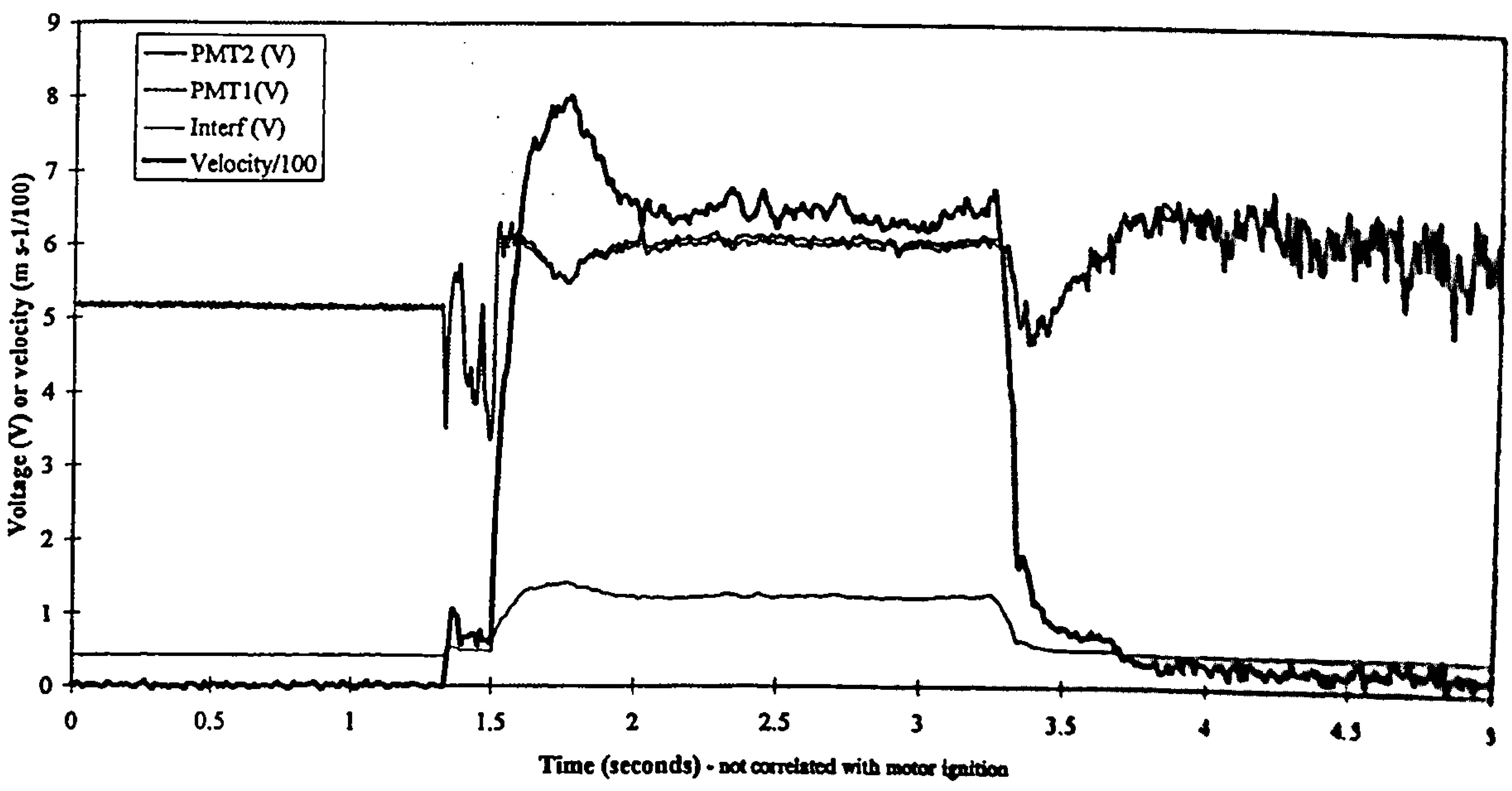


Figure 6.43 Interferometer and PMT outputs for Mini motor Firing M24 (D type, 18mm)

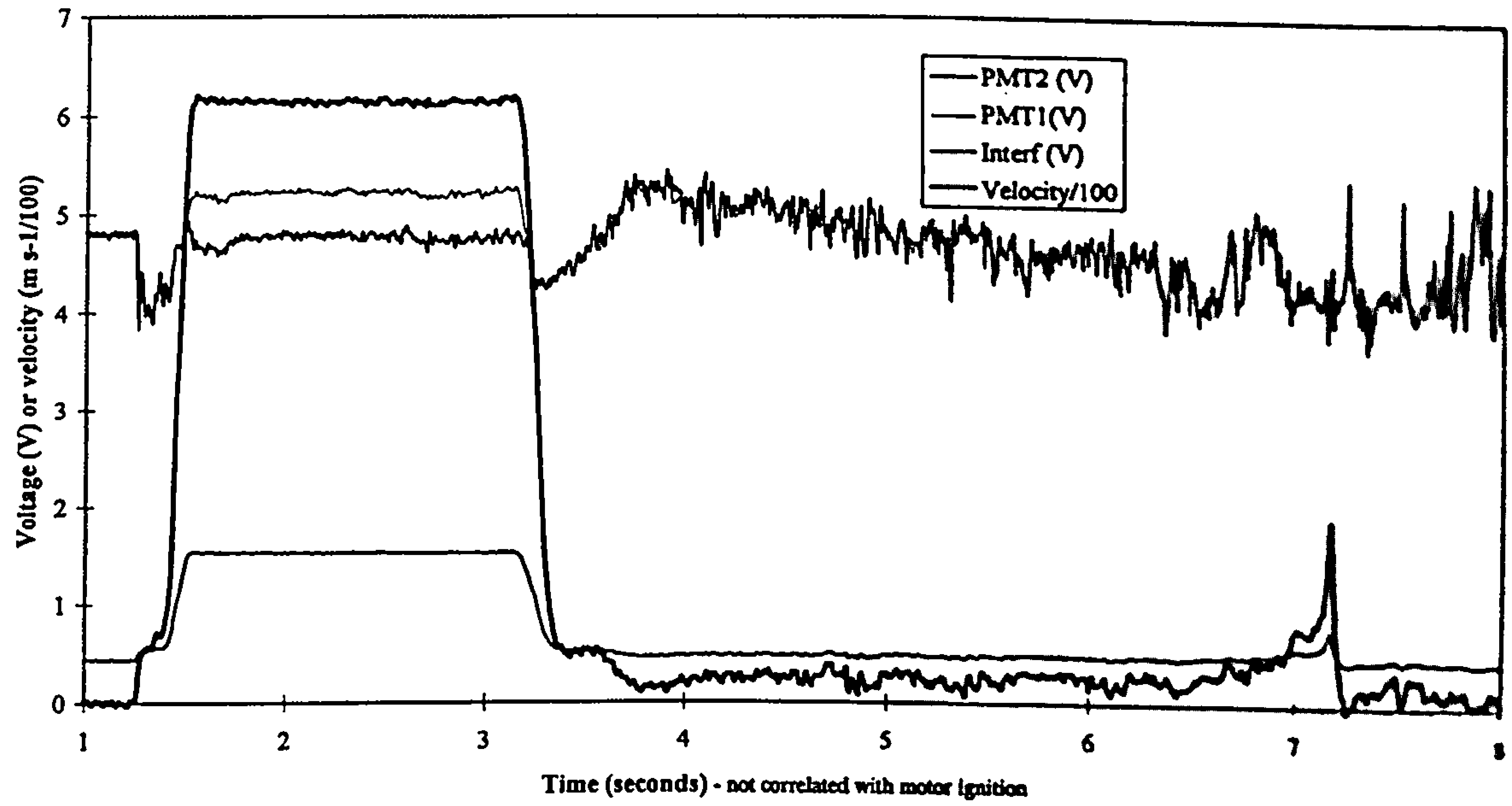


Figure 6.44 Outputs for Mini motor Firing M16, showing the dead region (D type, 18mm)

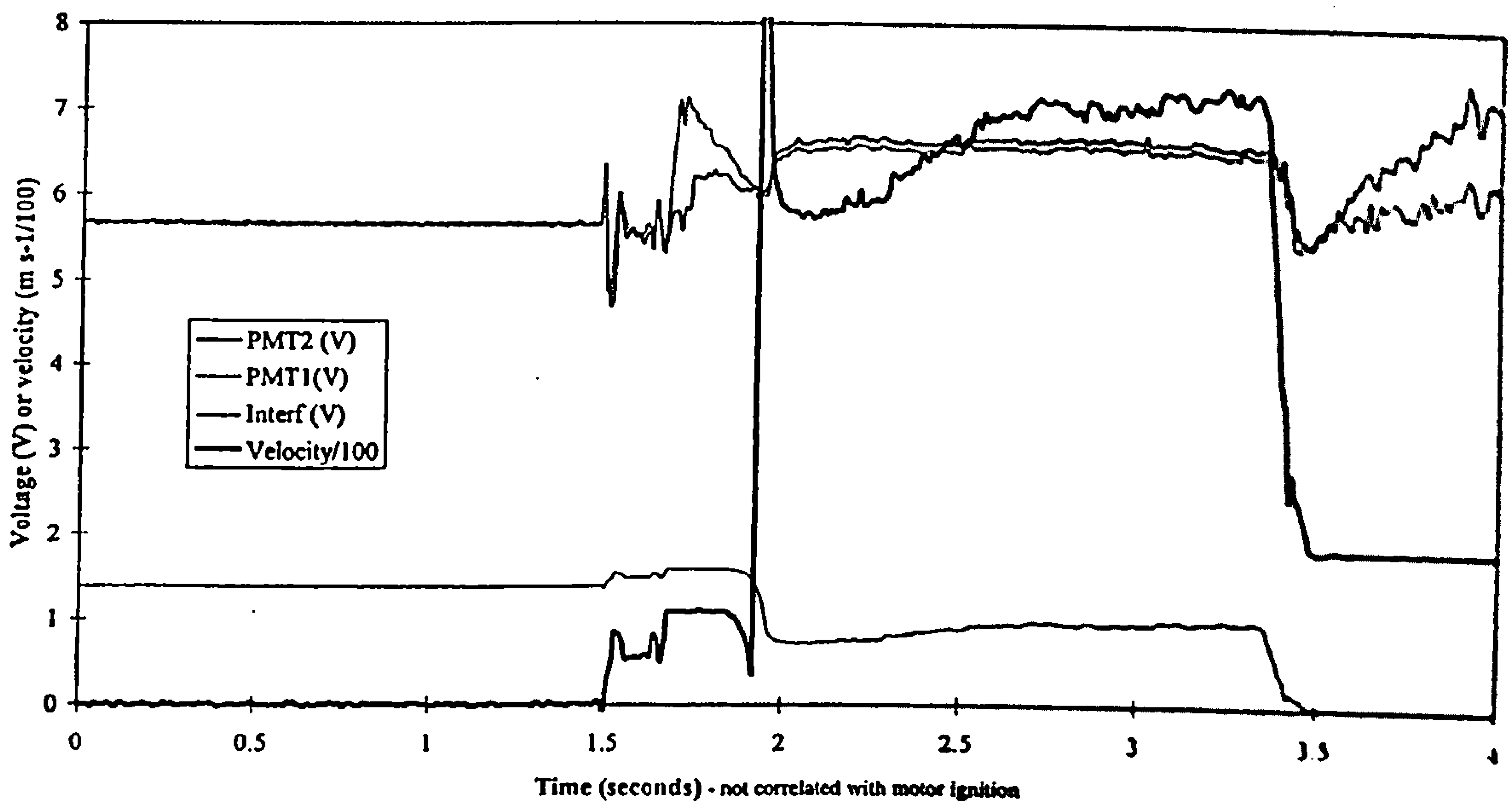


Figure 6.45 Outputs for Mini motor Firing M31, showing roll over (D type, 18mm)

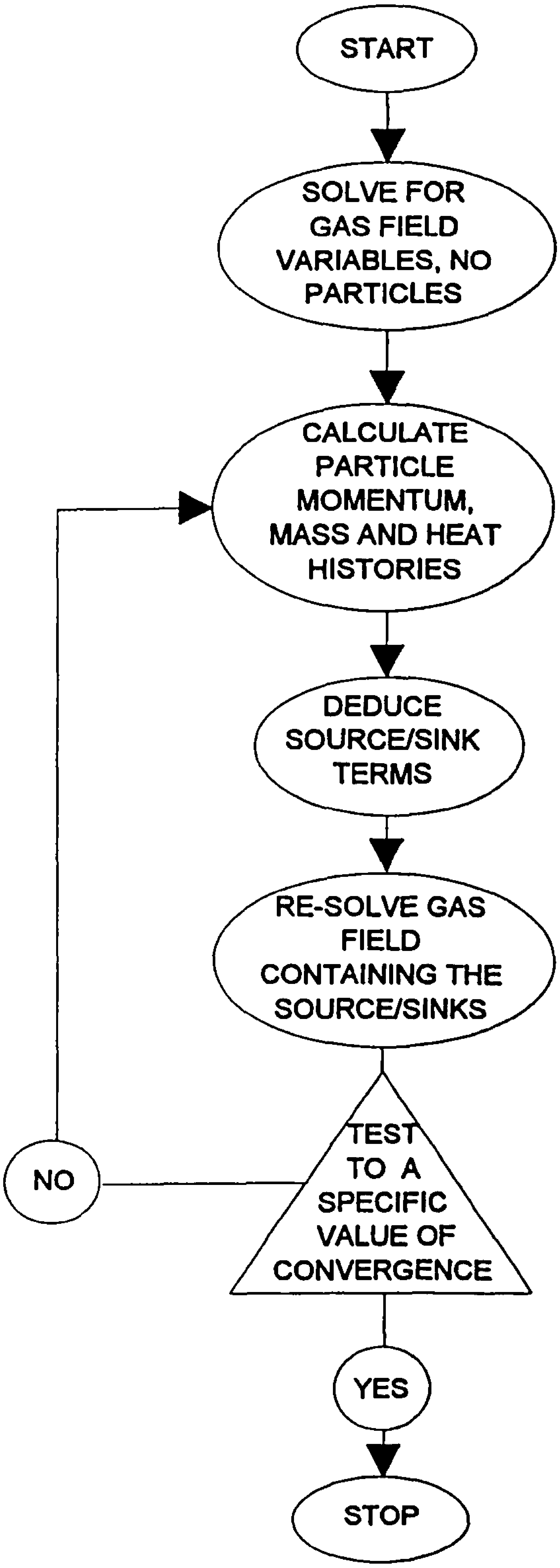


Figure 7.1 Schematic of GENTRA solution procedure

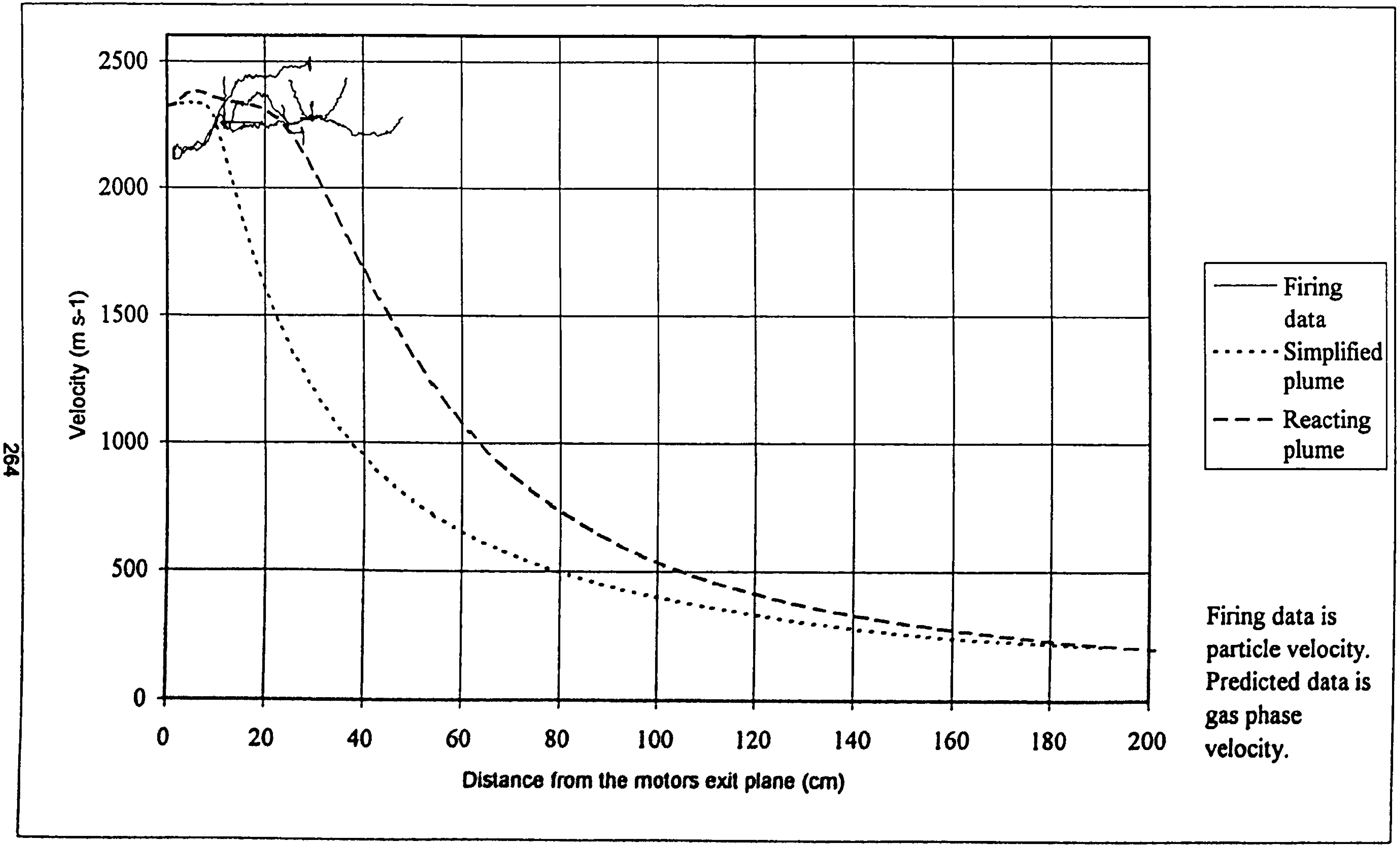


Figure 7.2 Predicted and experimental centre line velocity profiles

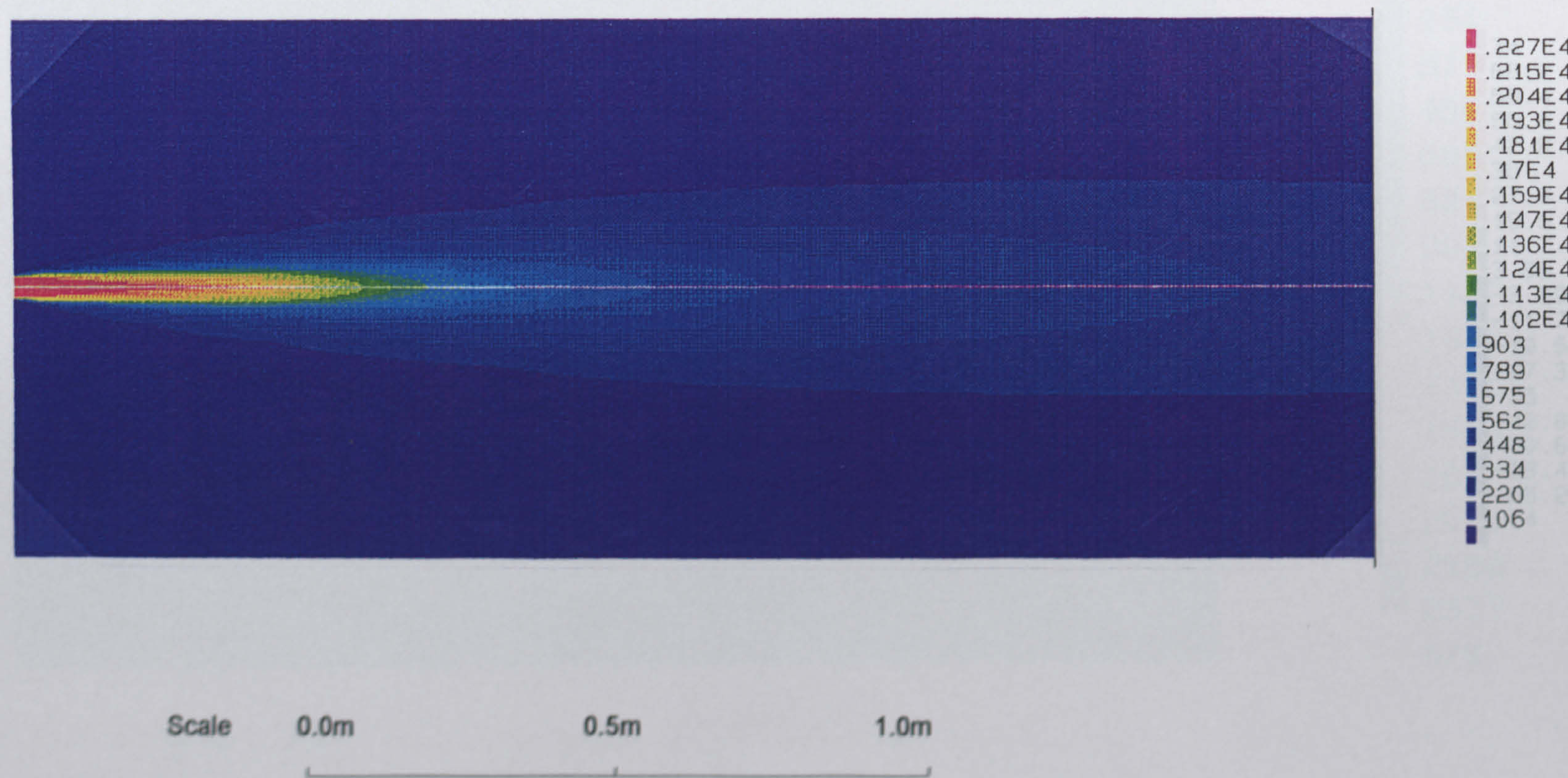


Figure 7.3 Axial gas velocities predicted using chemically reacting PHOENICS

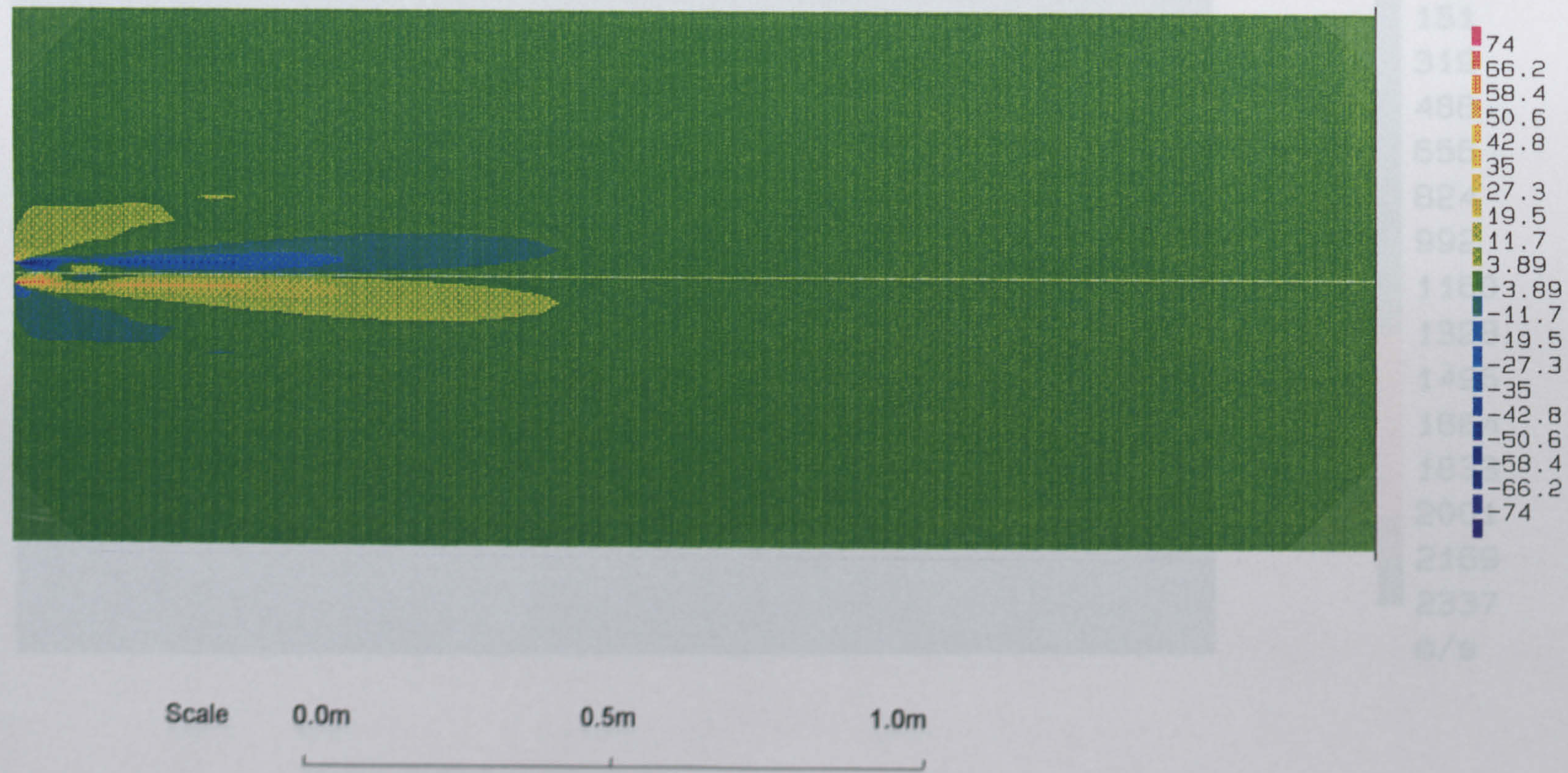


Figure 7.4 Radial gas velocities predicted using chemically reacting PHOENICS

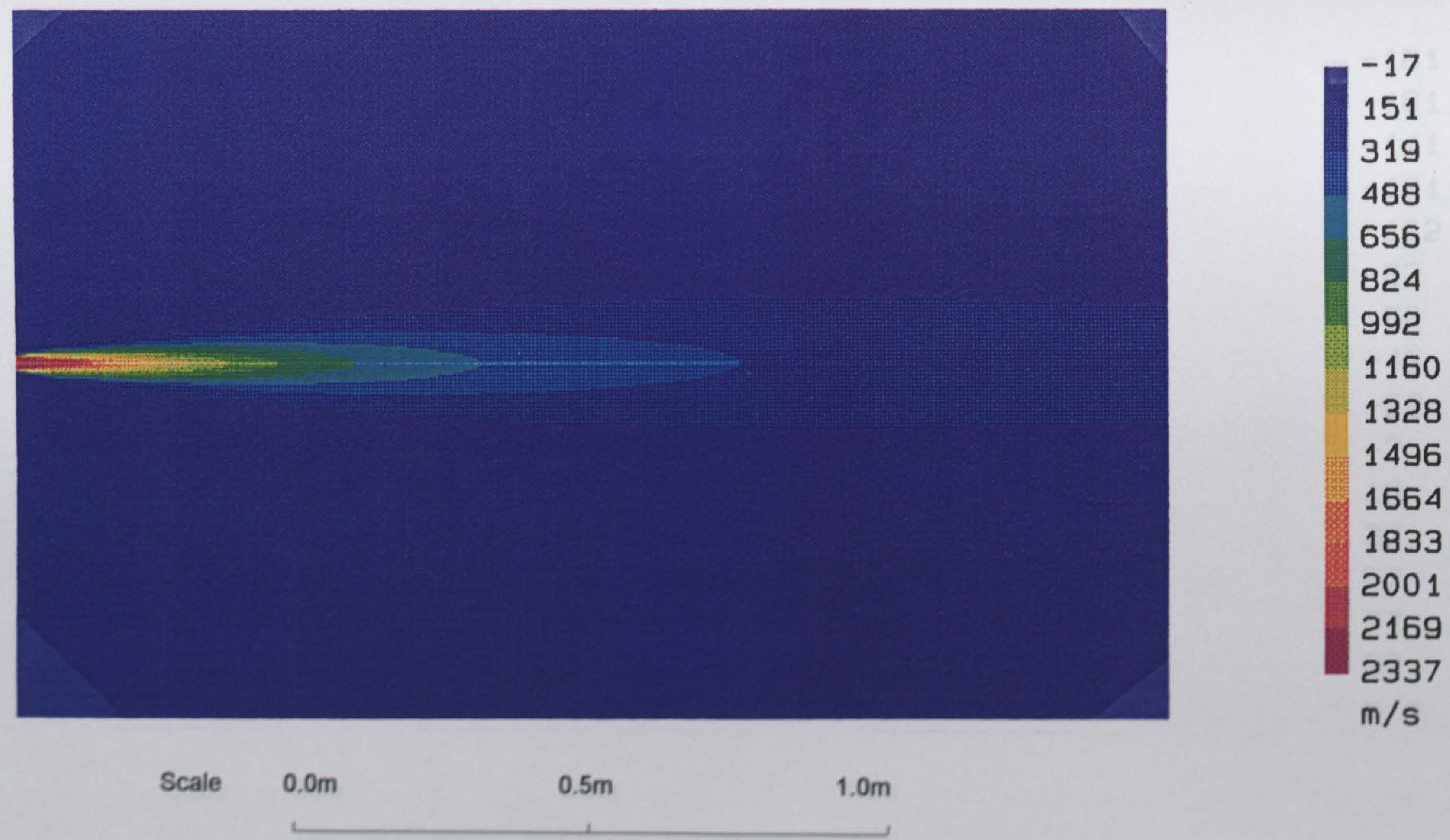


Figure 7.5 Axial gas velocities predicted using standard PHOENICS (simplified plume)

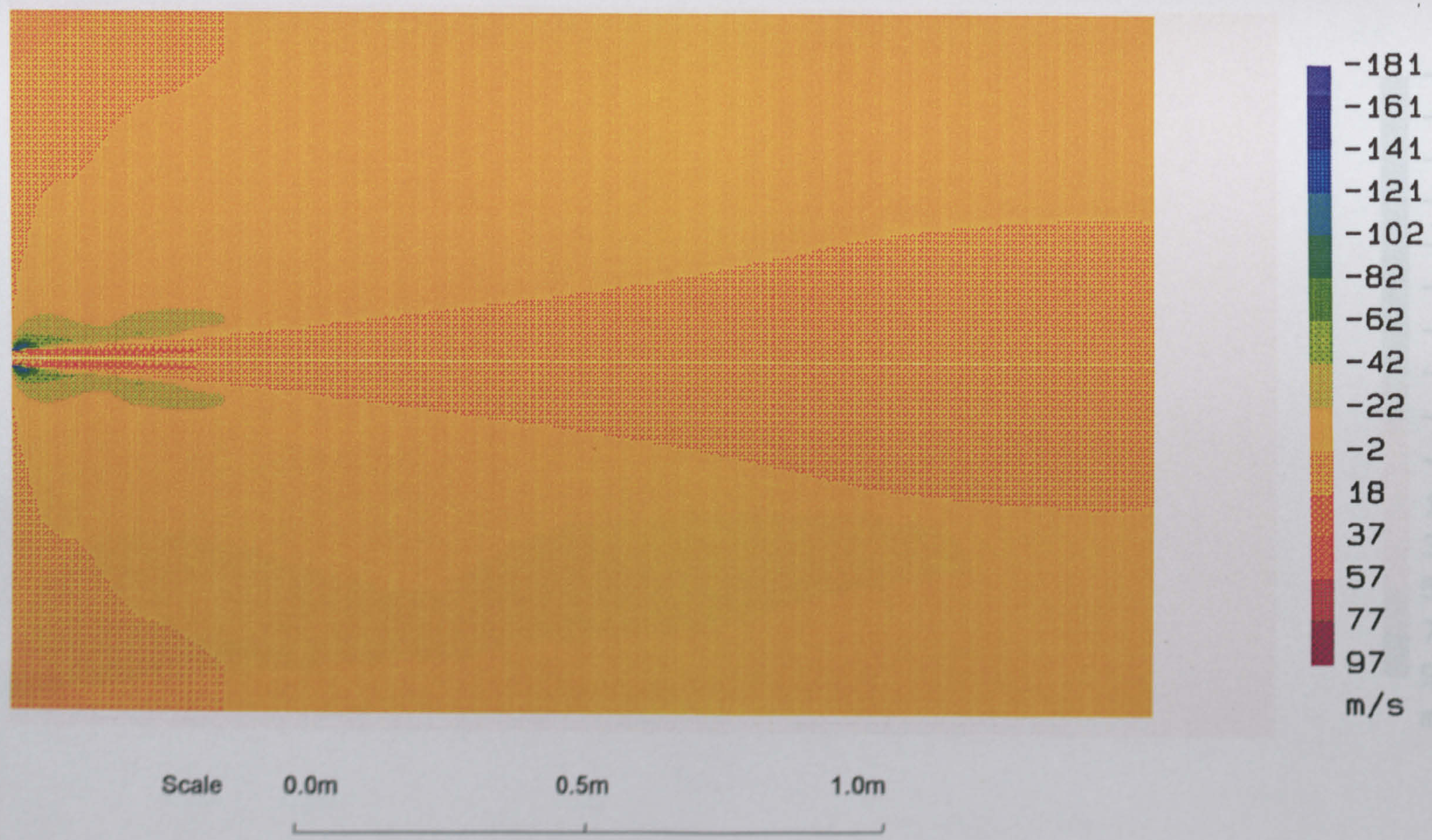


Figure 7.6 Radial gas velocities predicted using standard PHOENICS (simplified plume)

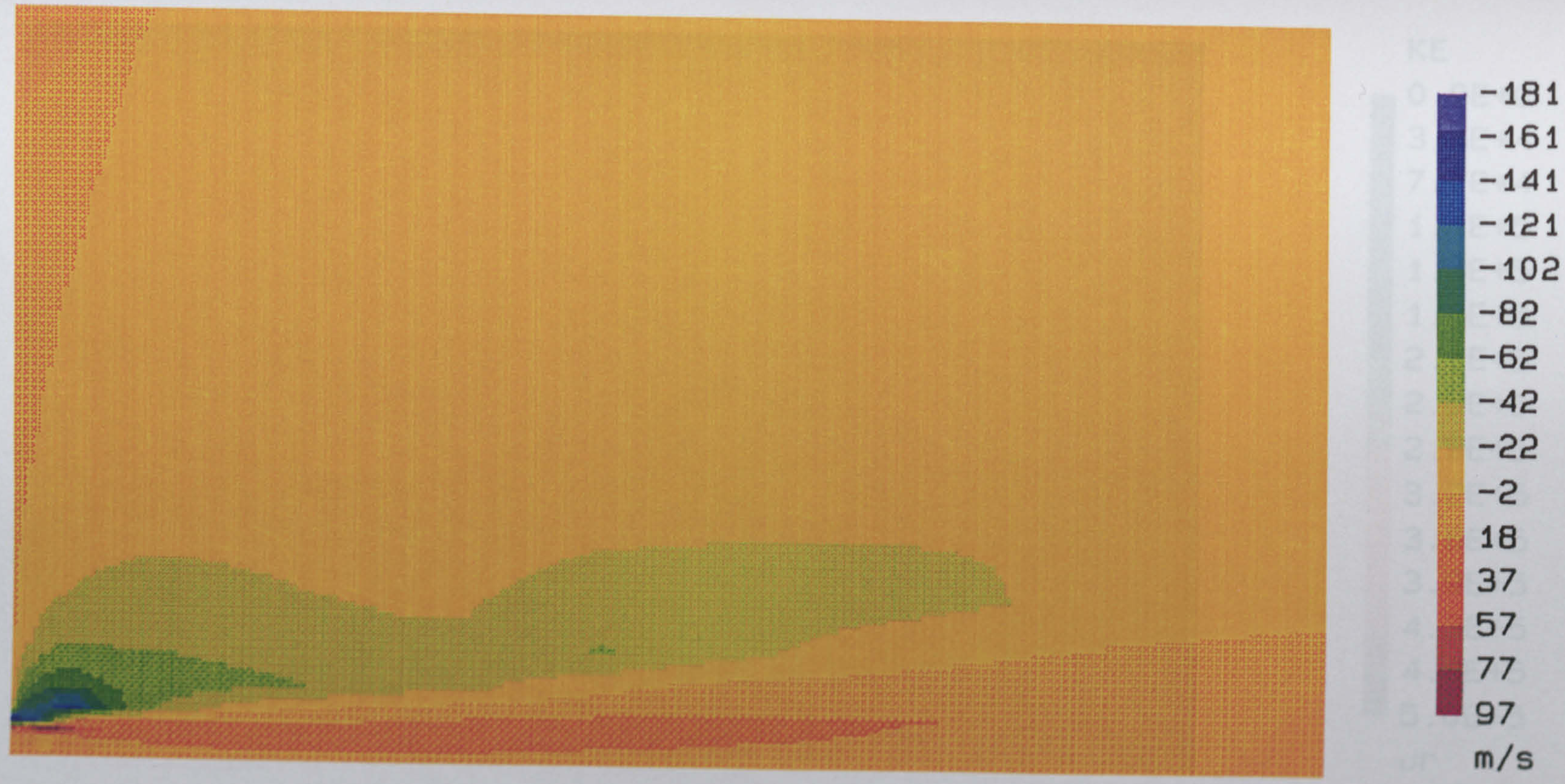


Figure 7.7 Detail of the radial gas velocities predicted using standard PHOENICS

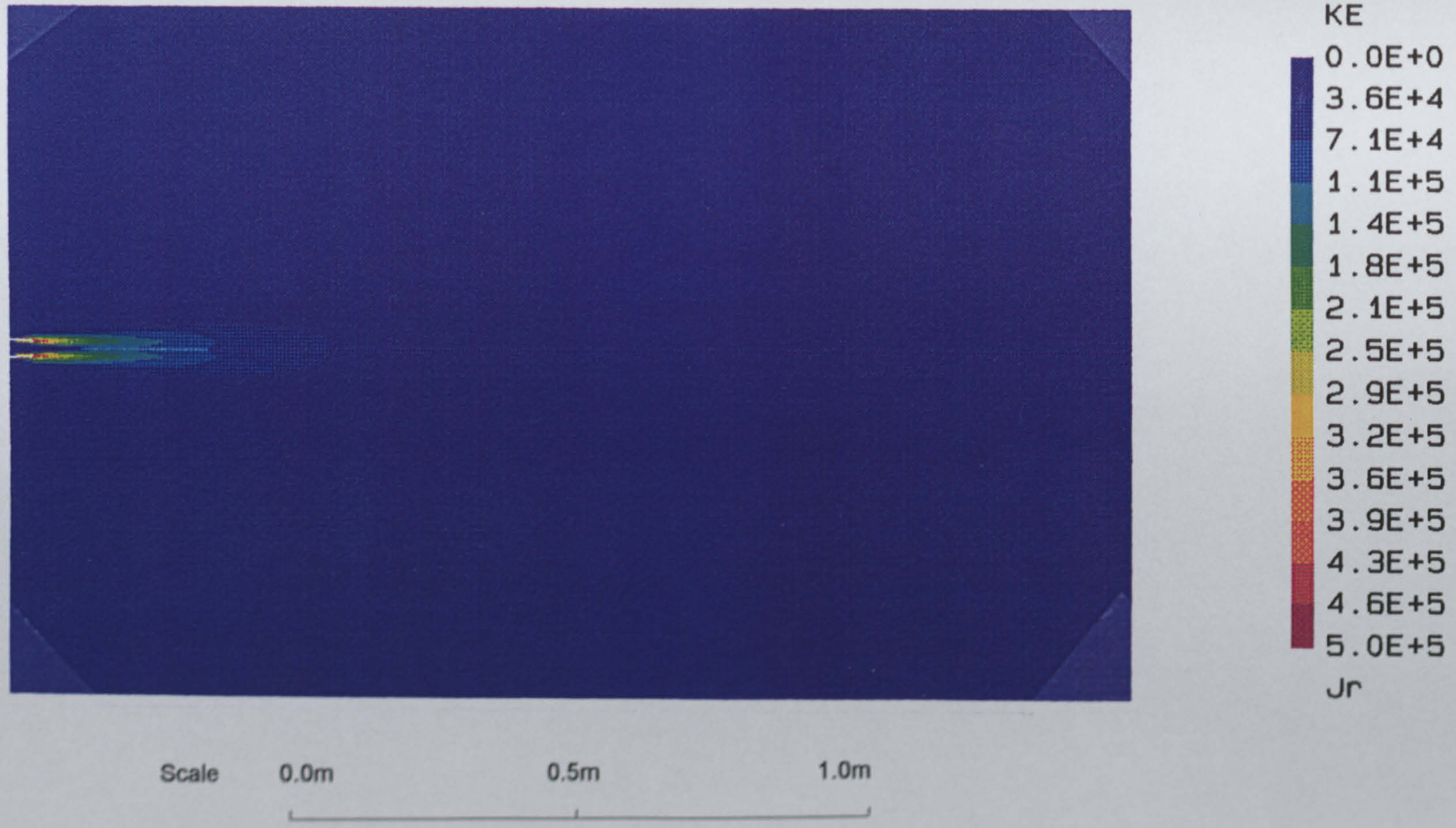


Figure 7.8 Turbulent intensities predicted using standard PHOENICS (simplified plume)

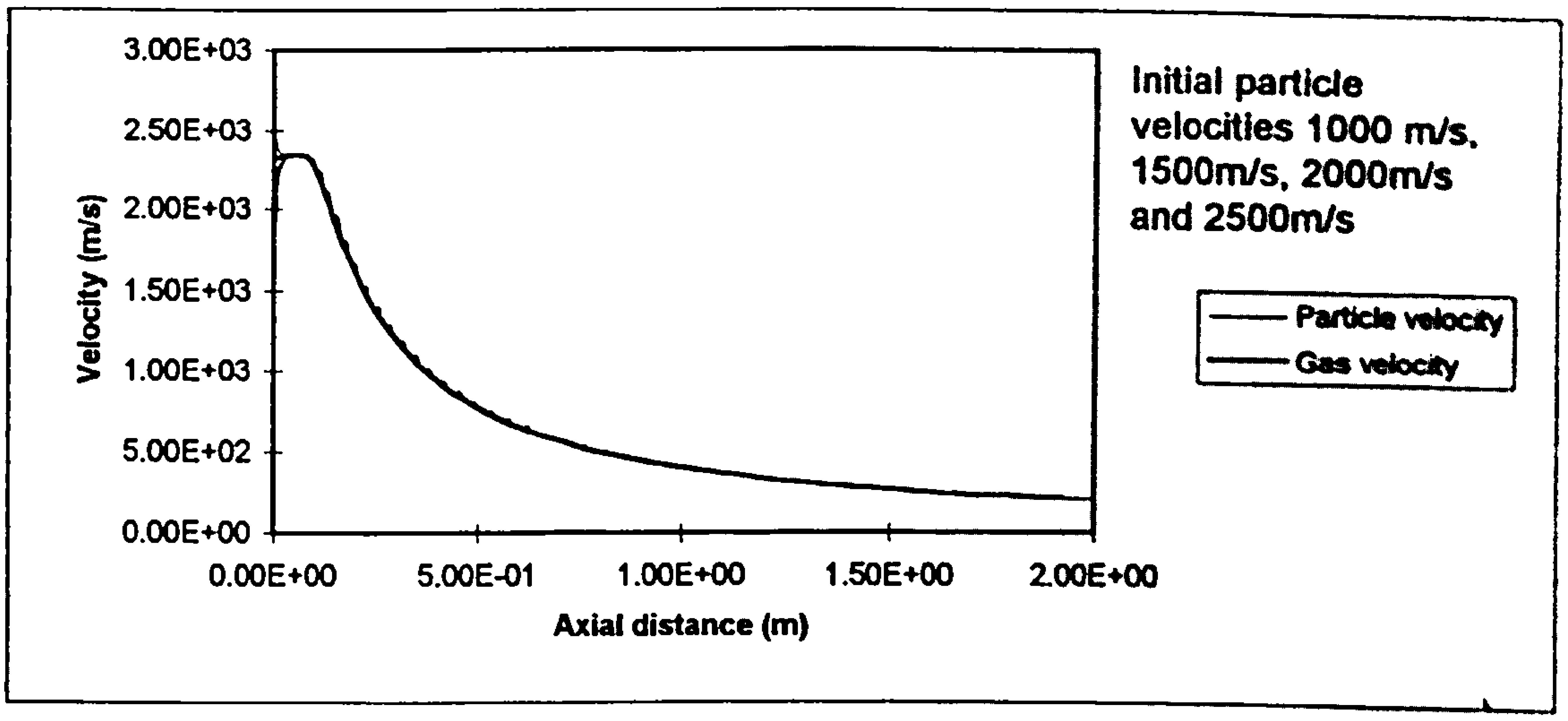


Figure 7.9 Predicted centre line particle velocities (0.5 micron)

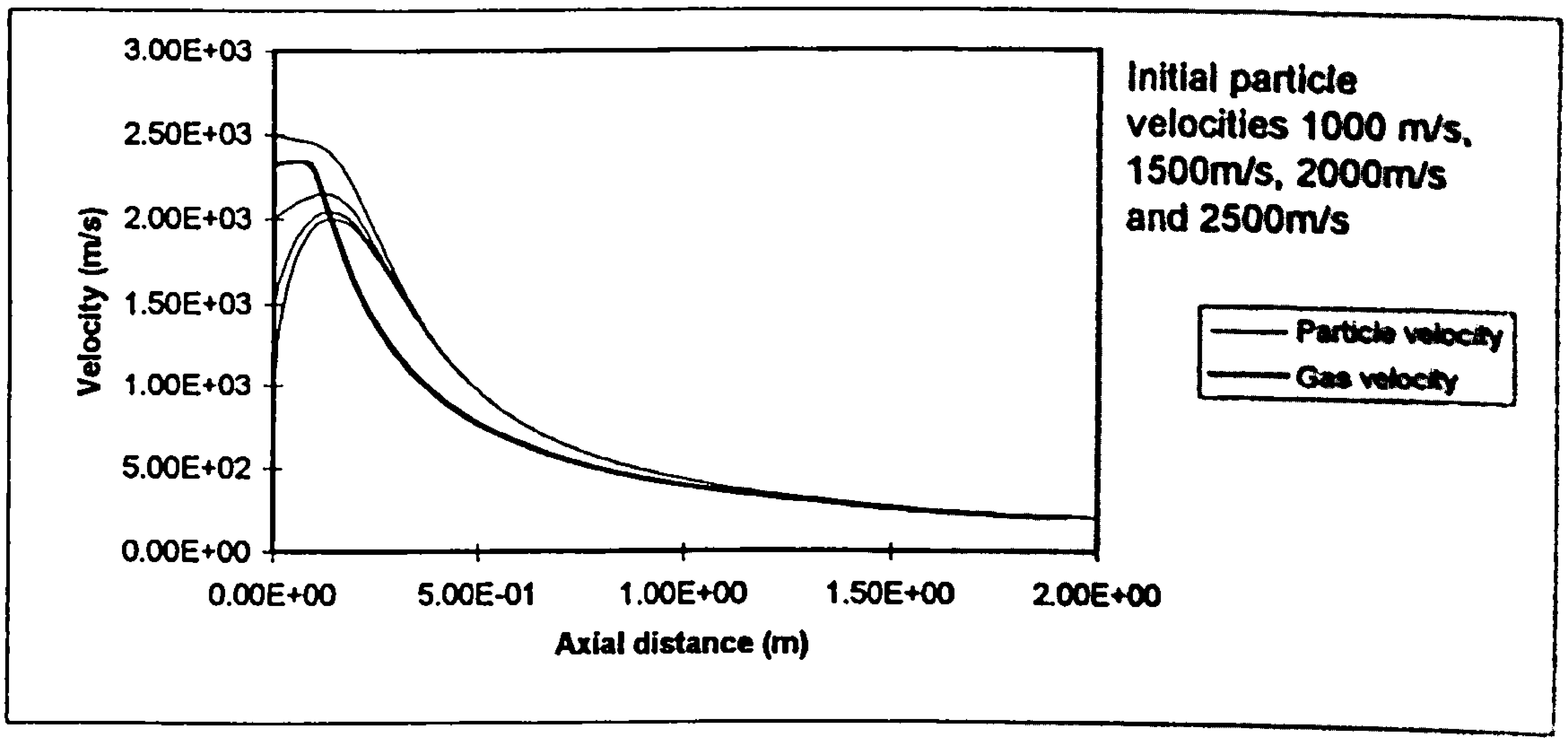


Figure 7.10 Predicted centre line particle velocities (4.0 micron)

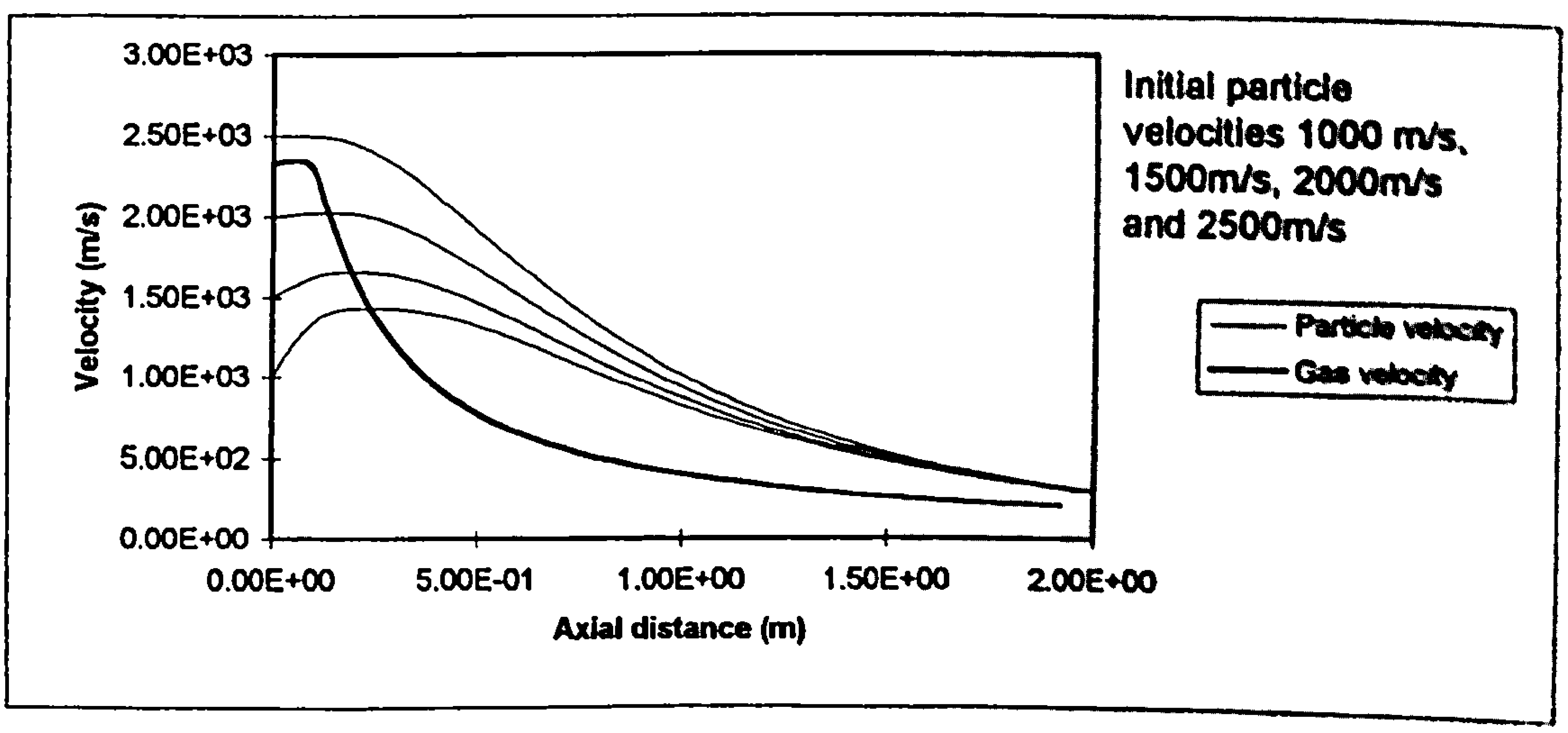


Figure 7.11 Predicted centre line particle velocities (20 micron)

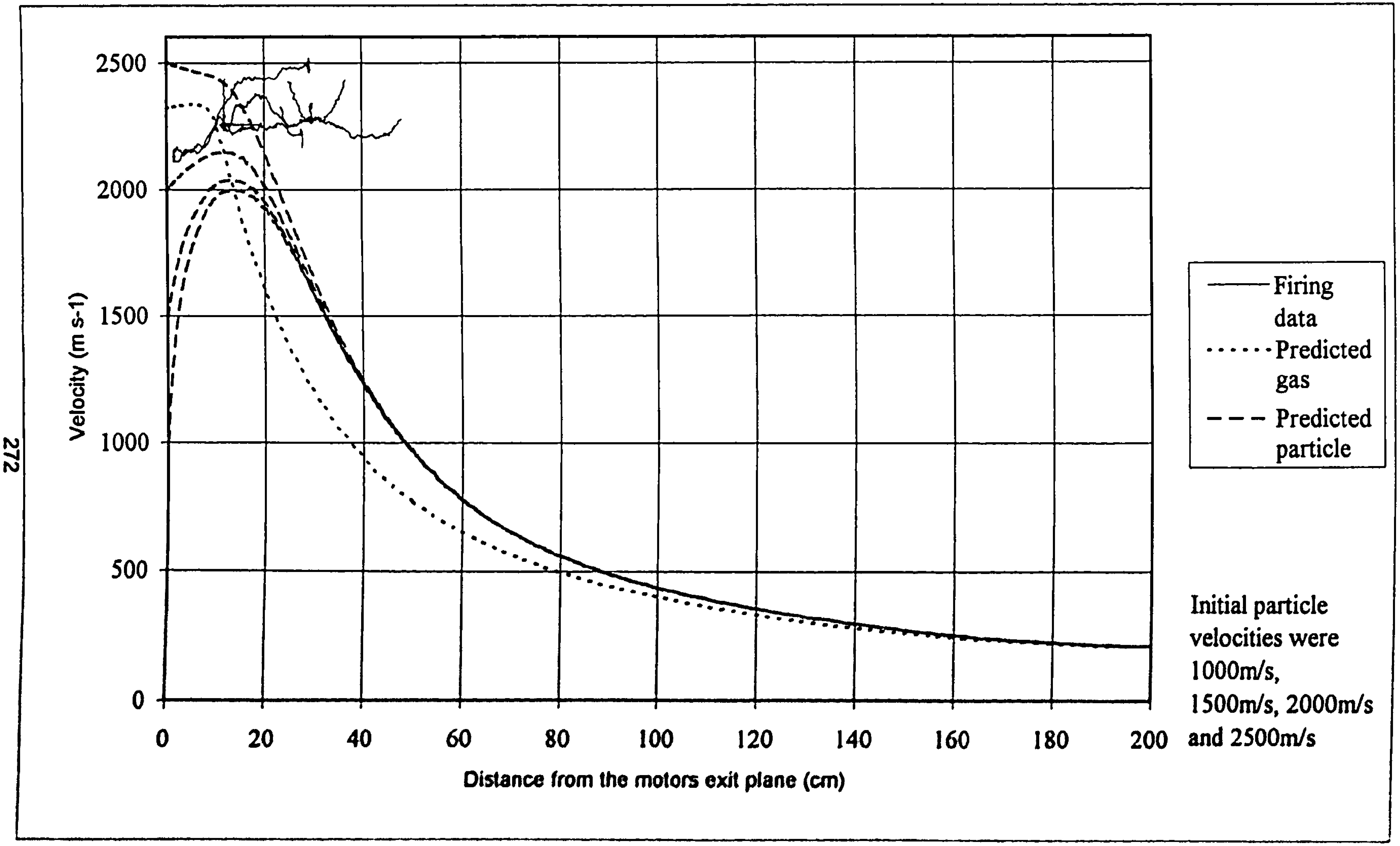


Figure 7.12 **Predicted and experimental centre line particle velocity profiles**

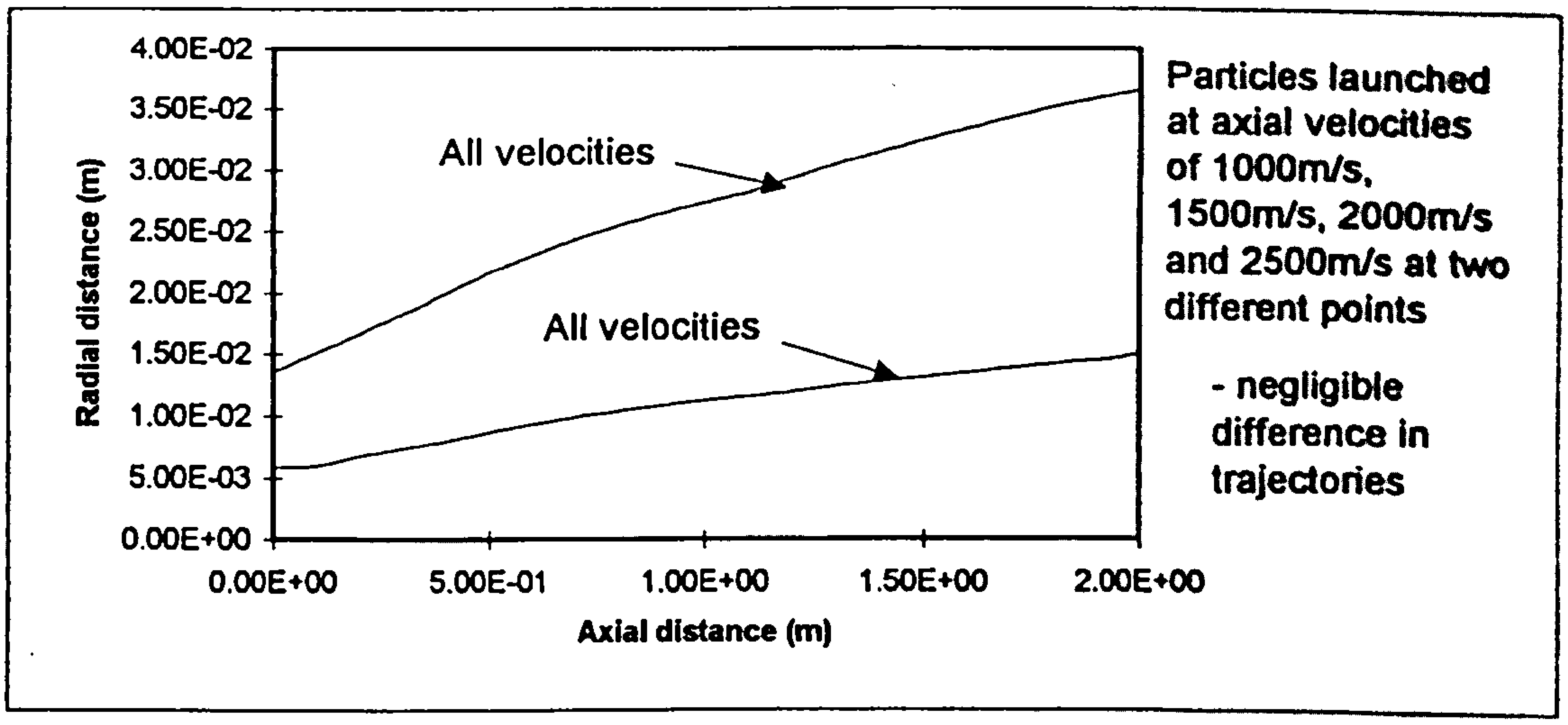


Figure 7.13 Predicted trajectories of 0.5 micron particles with varying axial velocity

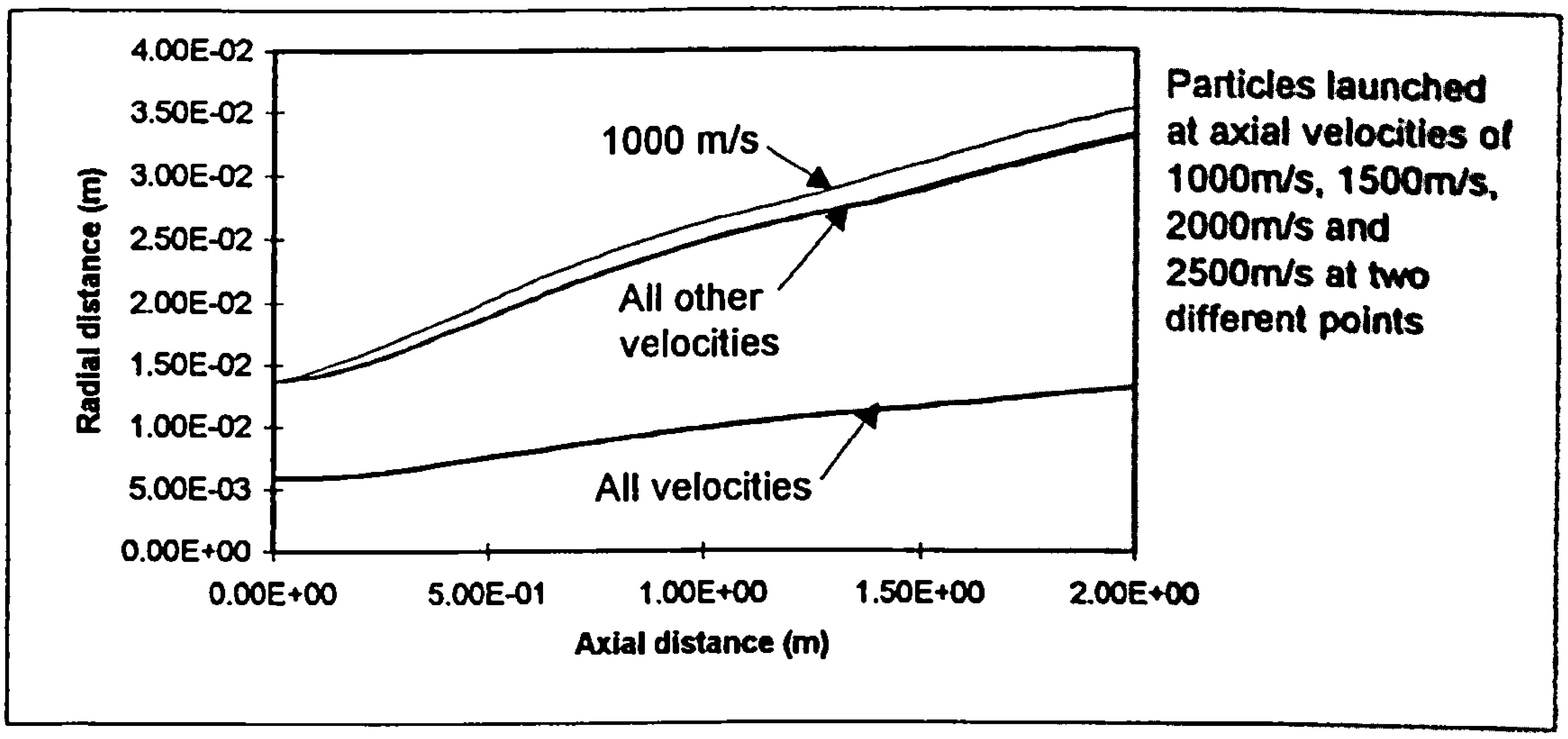


Figure 7.14 Predicted trajectories of 4 micron particles with varying axial velocity

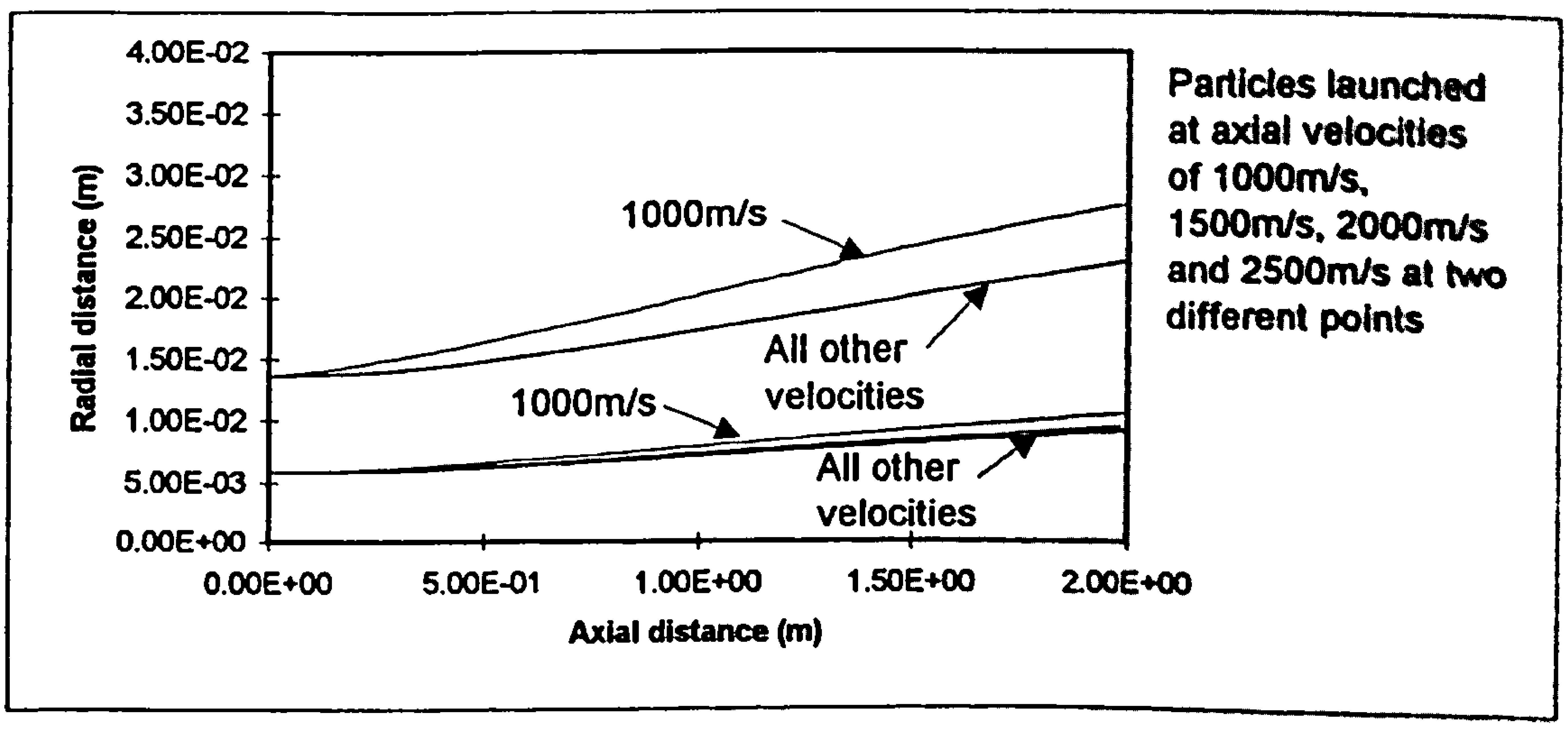


Figure 7.15 Predicted trajectories of 20 micron particles with varying axial velocity

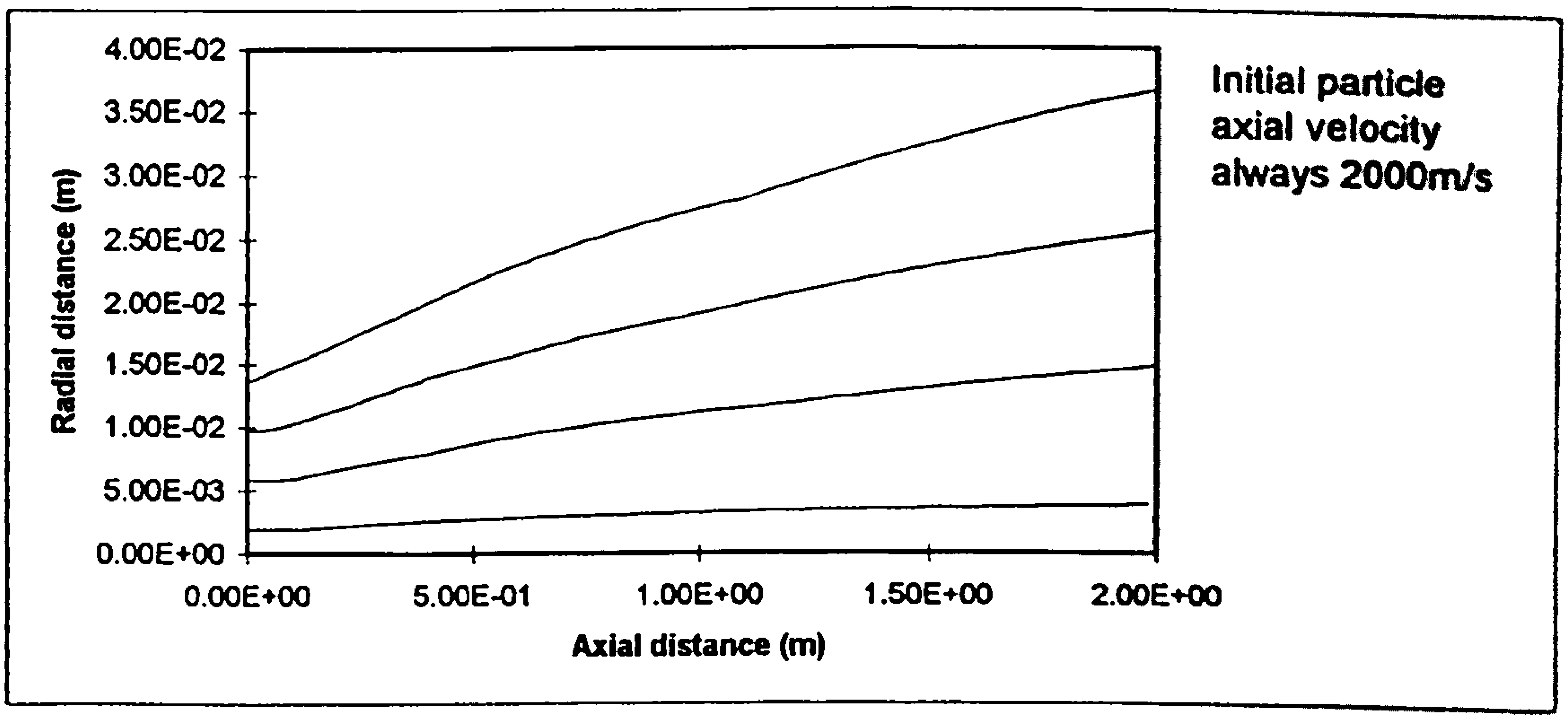


Figure 7.16 Predicted trajectories of 0.5 micron particles (initial axial velocity)

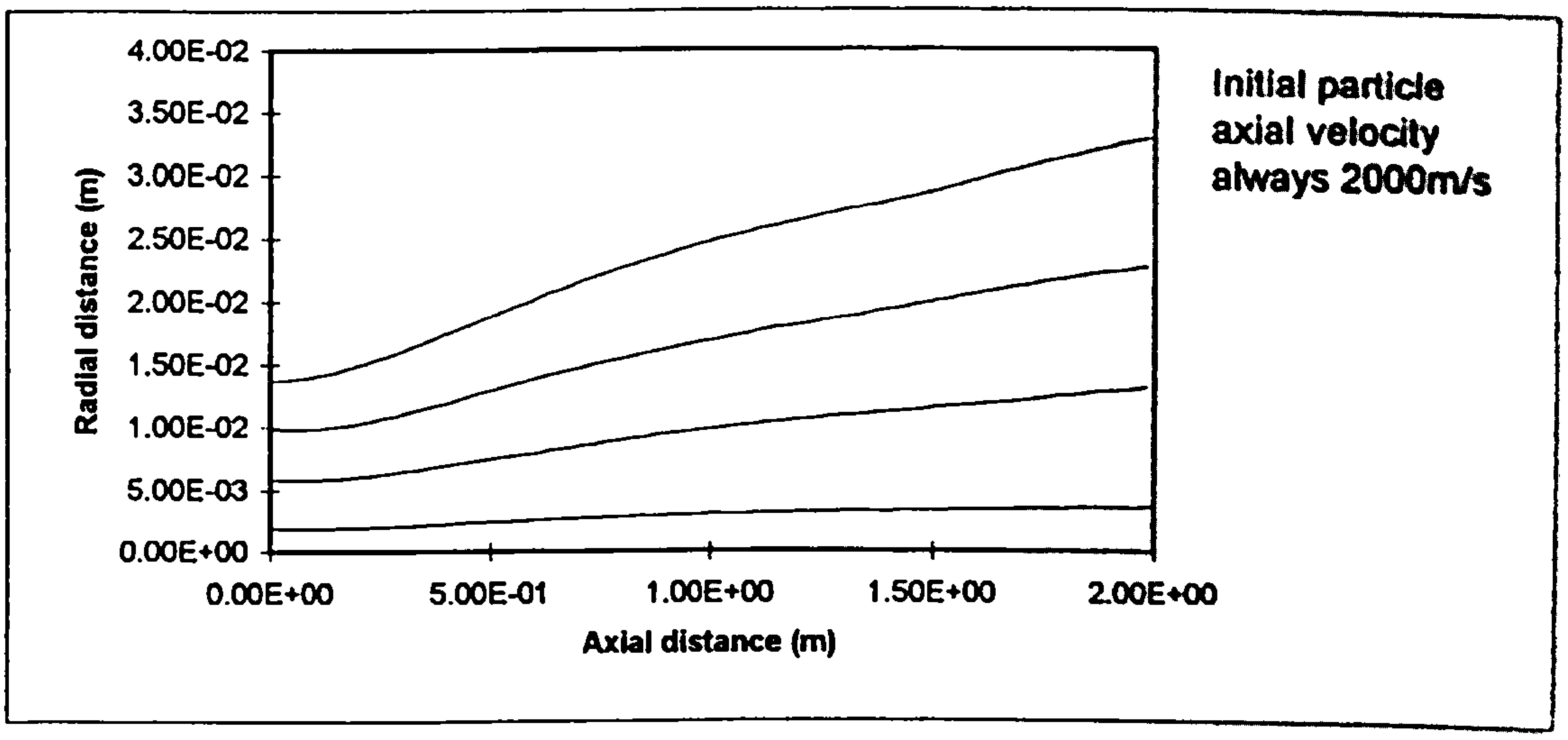


Figure 7.17 Predicted trajectories of 4 micron particles (initial axial velocity)

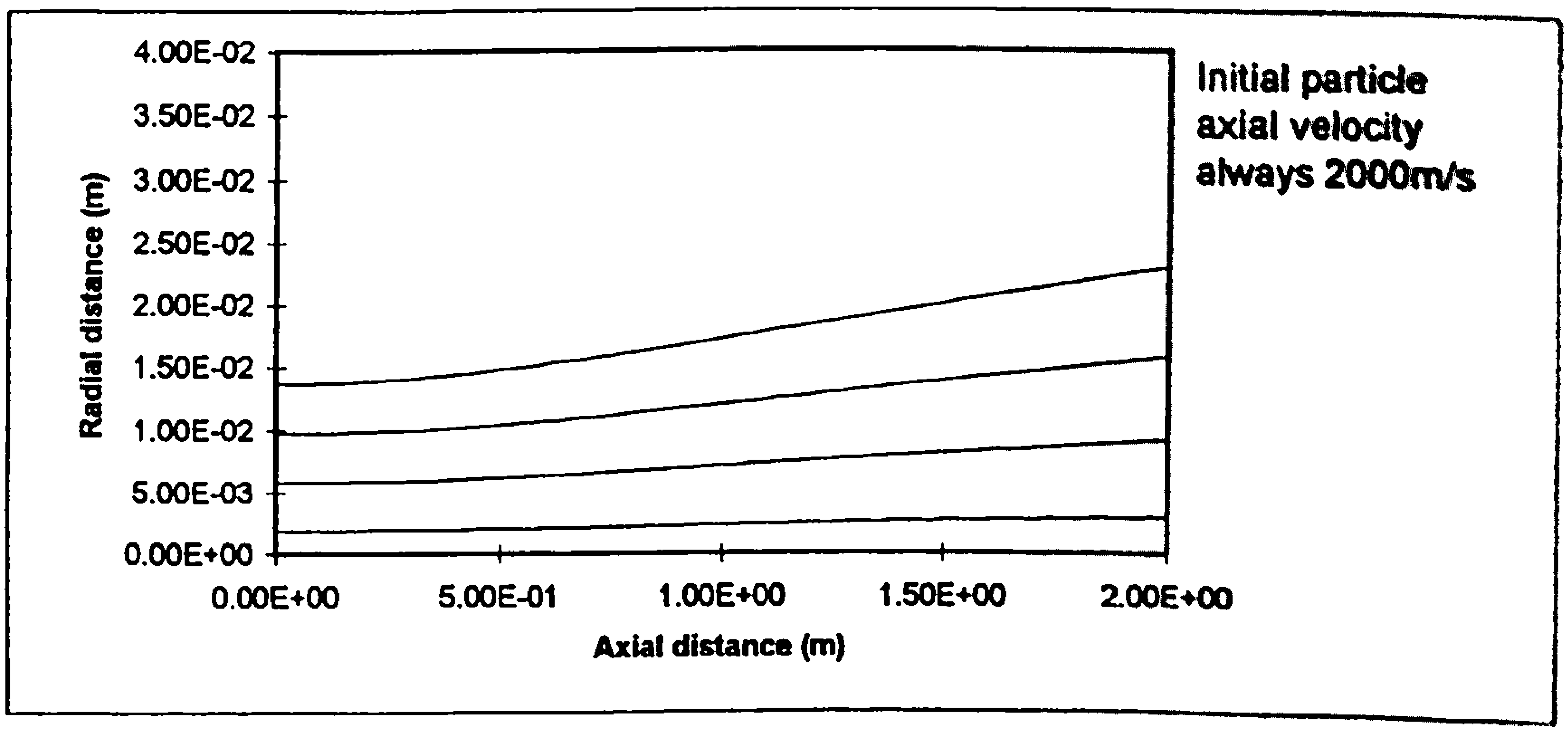


Figure 7.18 Predicted trajectories of 20 micron particles (initial axial velocity)

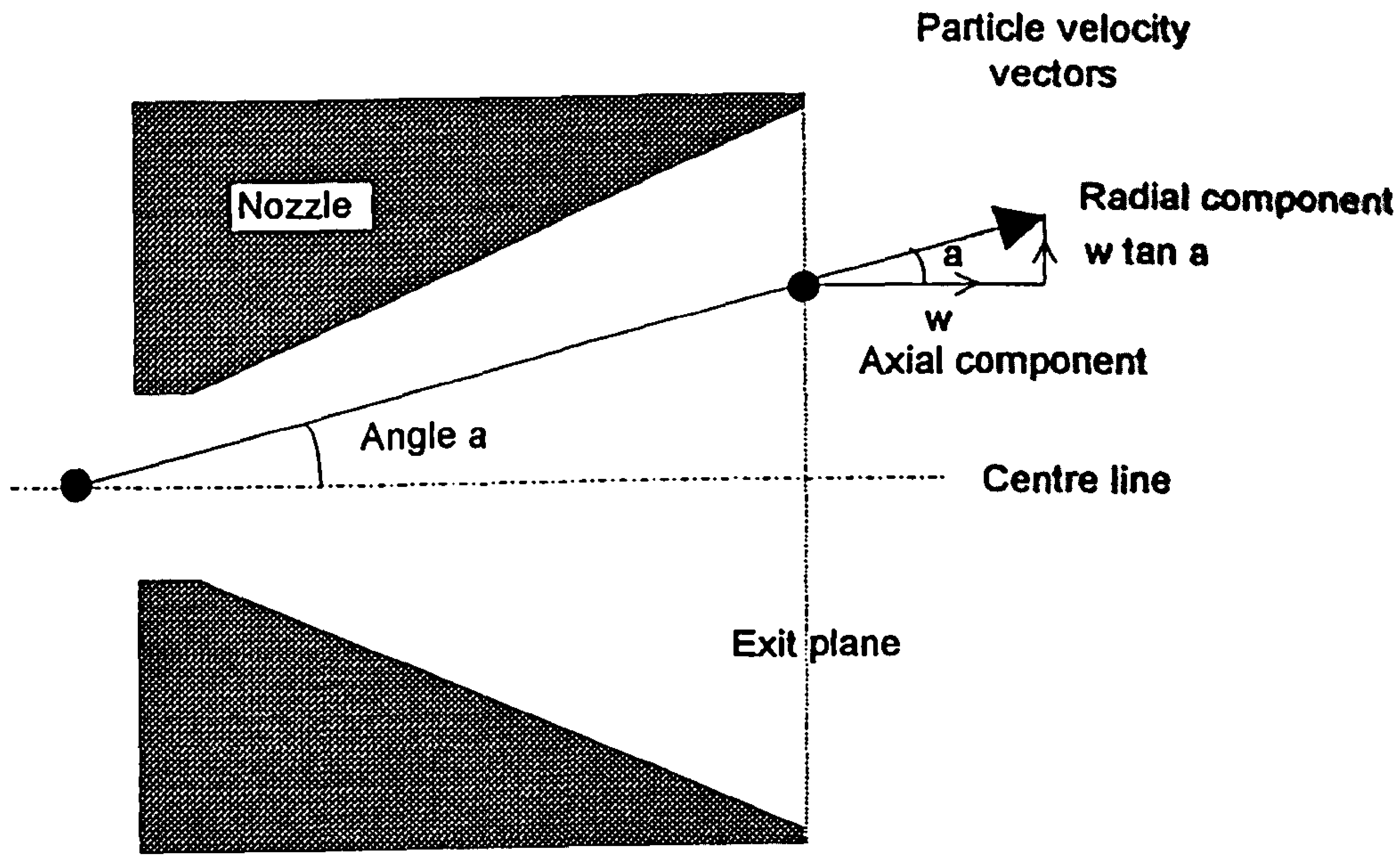


Figure 7.19 Schematic of radial velocity calculation

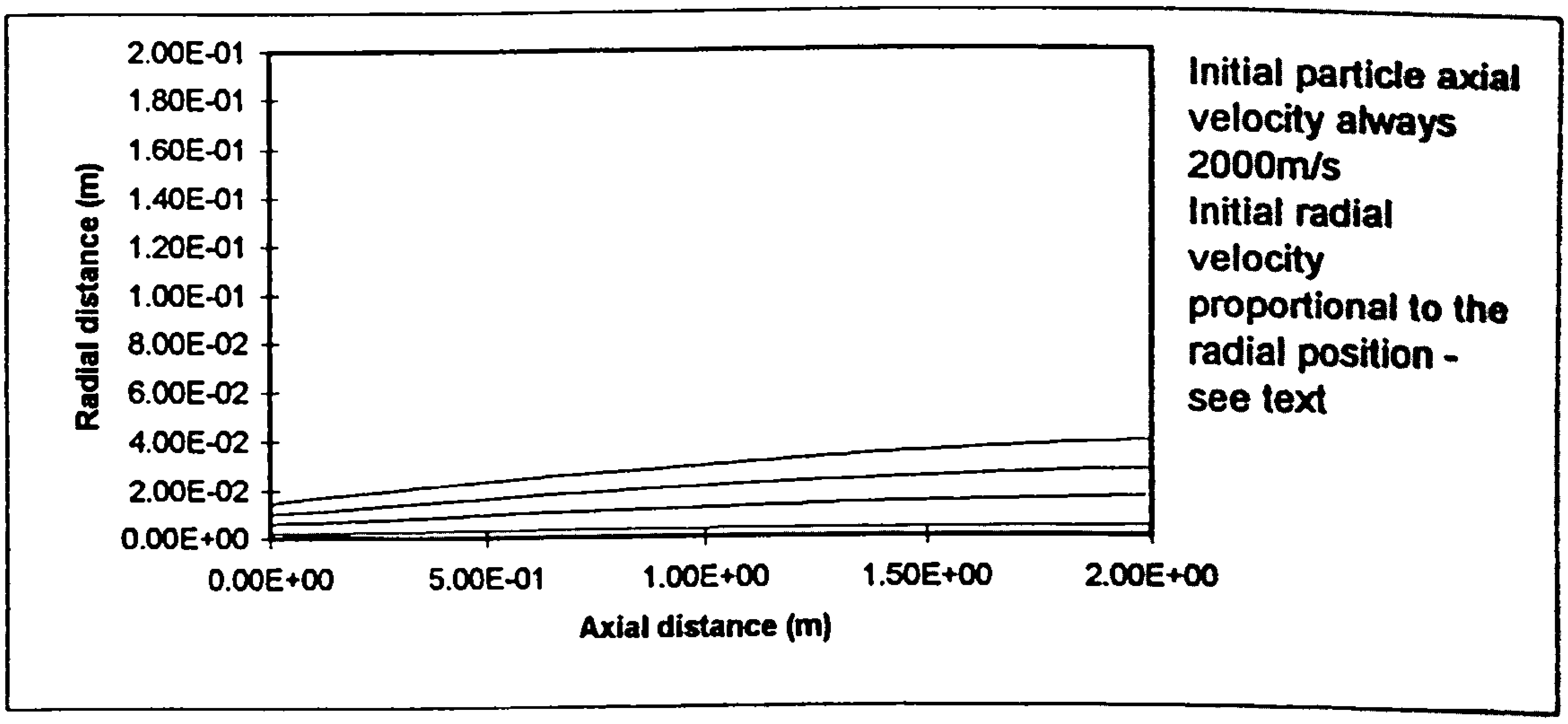


Figure 7.20 Predicted trajectories of 0.5 micron particles (initial radial velocity)

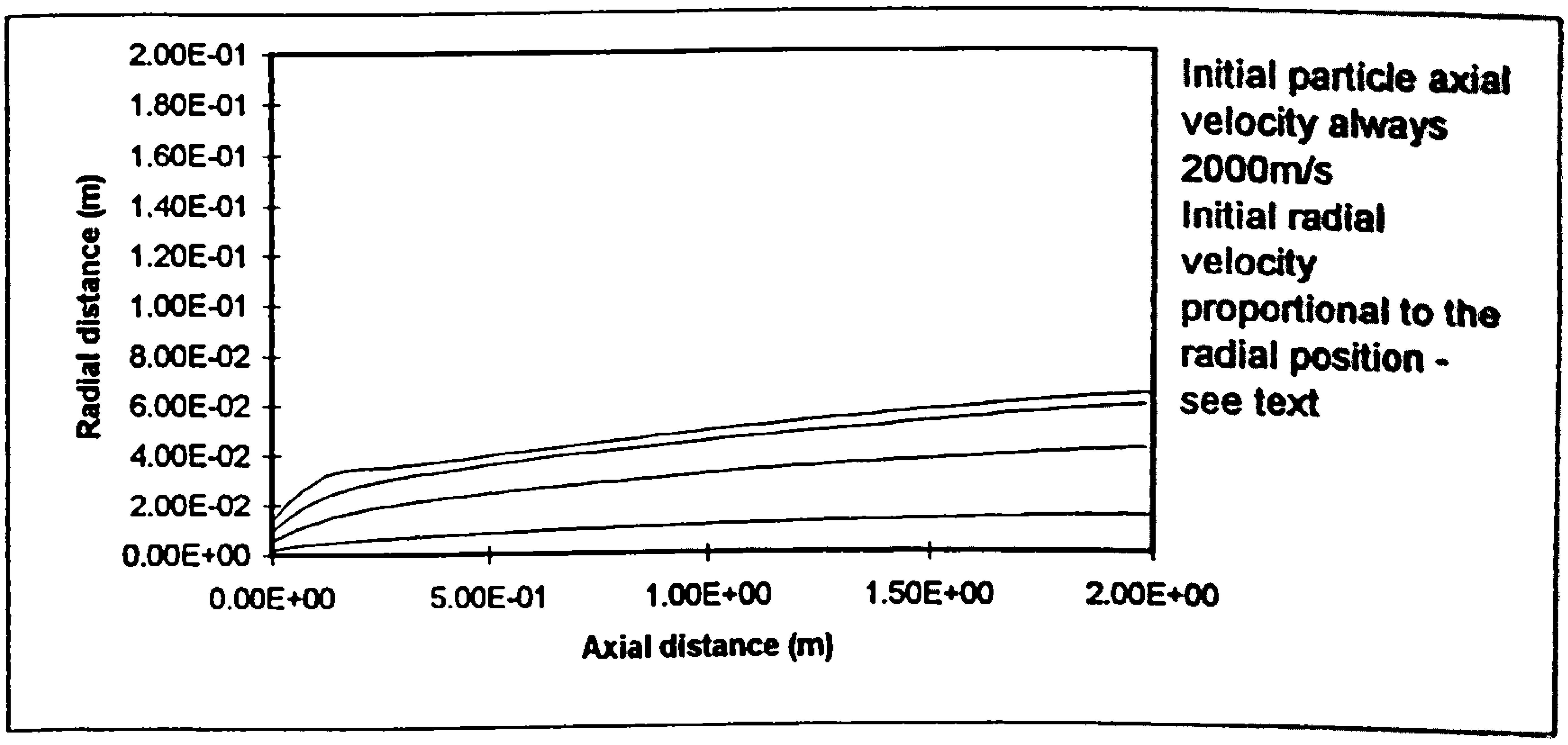


Figure 7.21 Predicted trajectories of 4.0 micron particles (initial radial velocity)

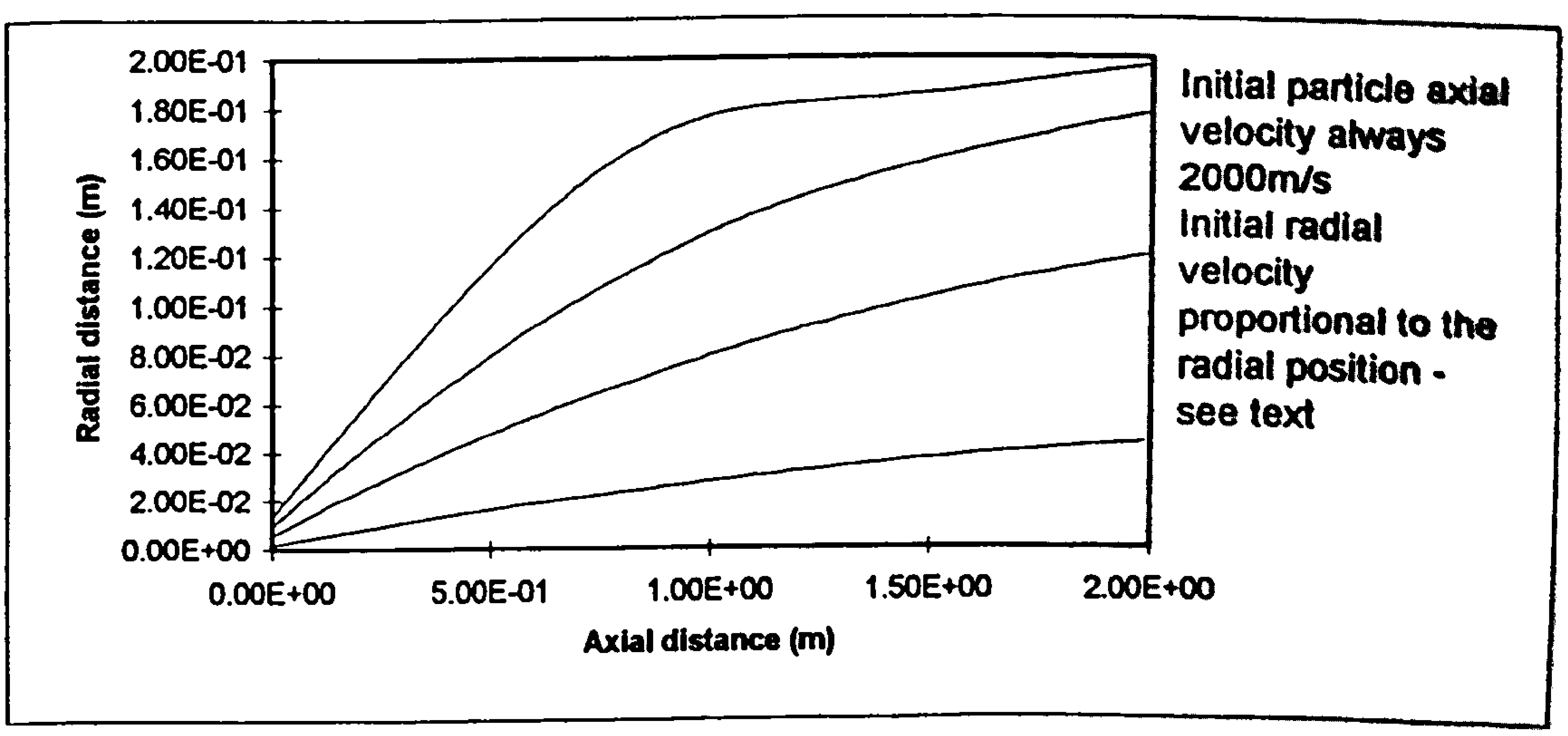


Figure 7.22 Predicted trajectories of 20 micron particles (initial radial velocity)

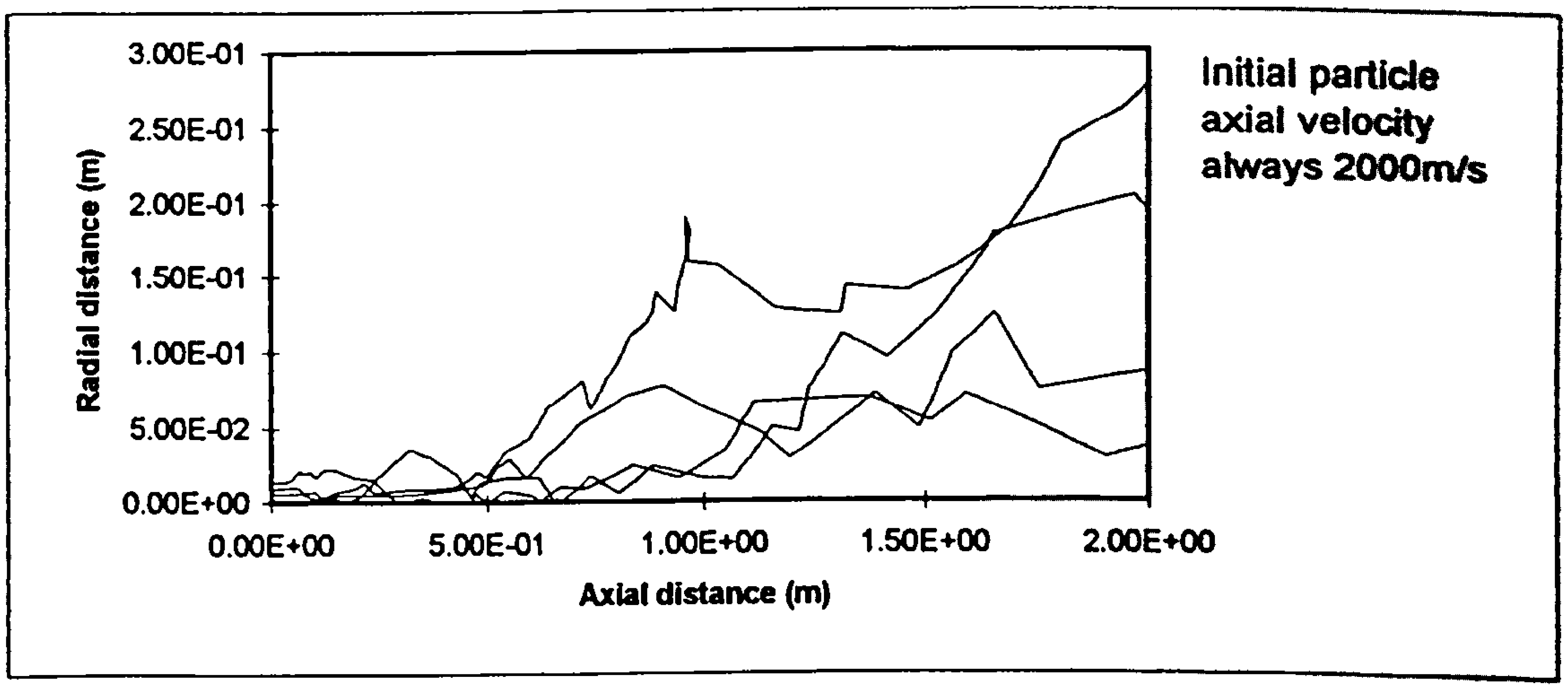


Figure 7.23 Predicted trajectories of 0.5 micron particles (with turbulence)

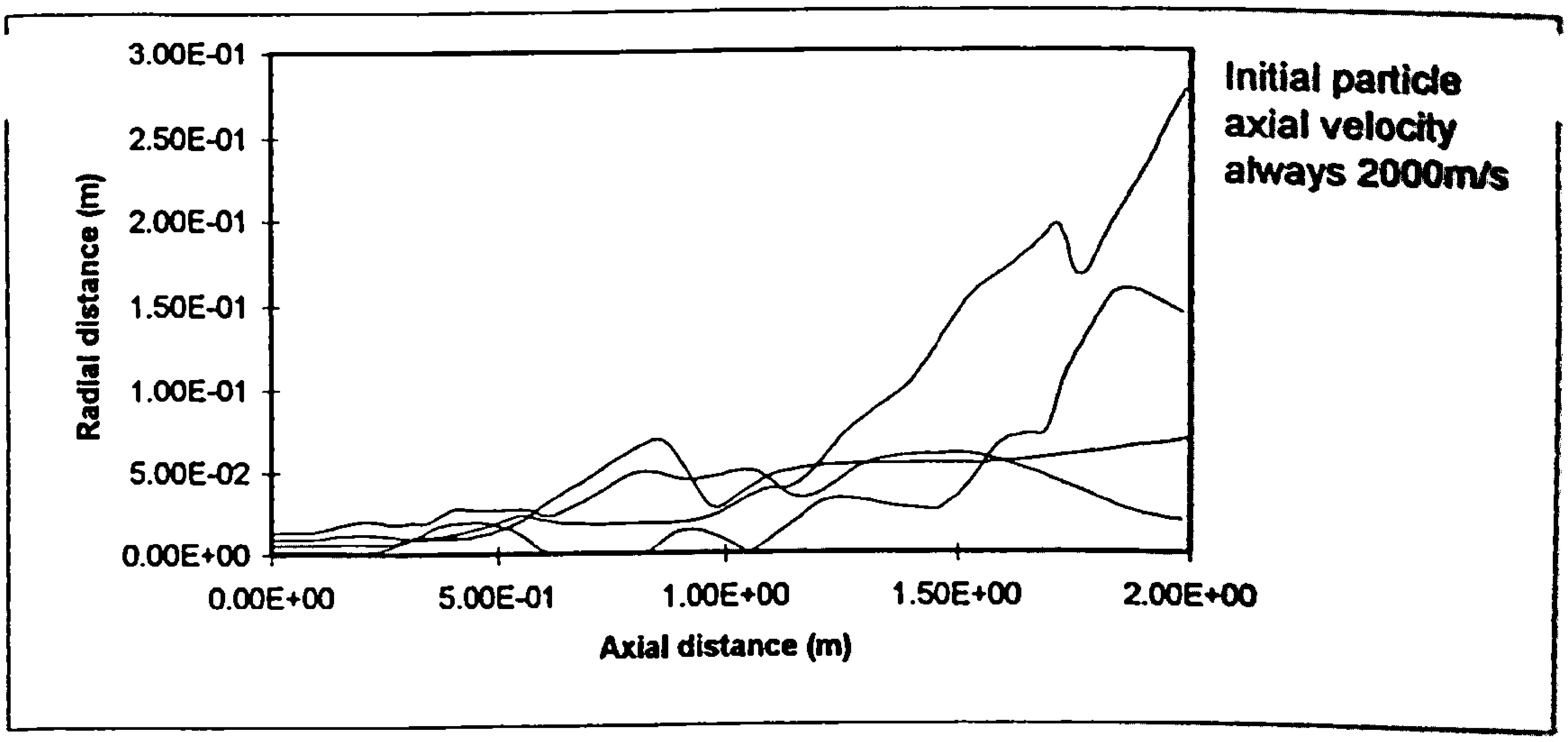


Figure 7.24 Predicted trajectories of 4.0 micron particles (with turbulence)

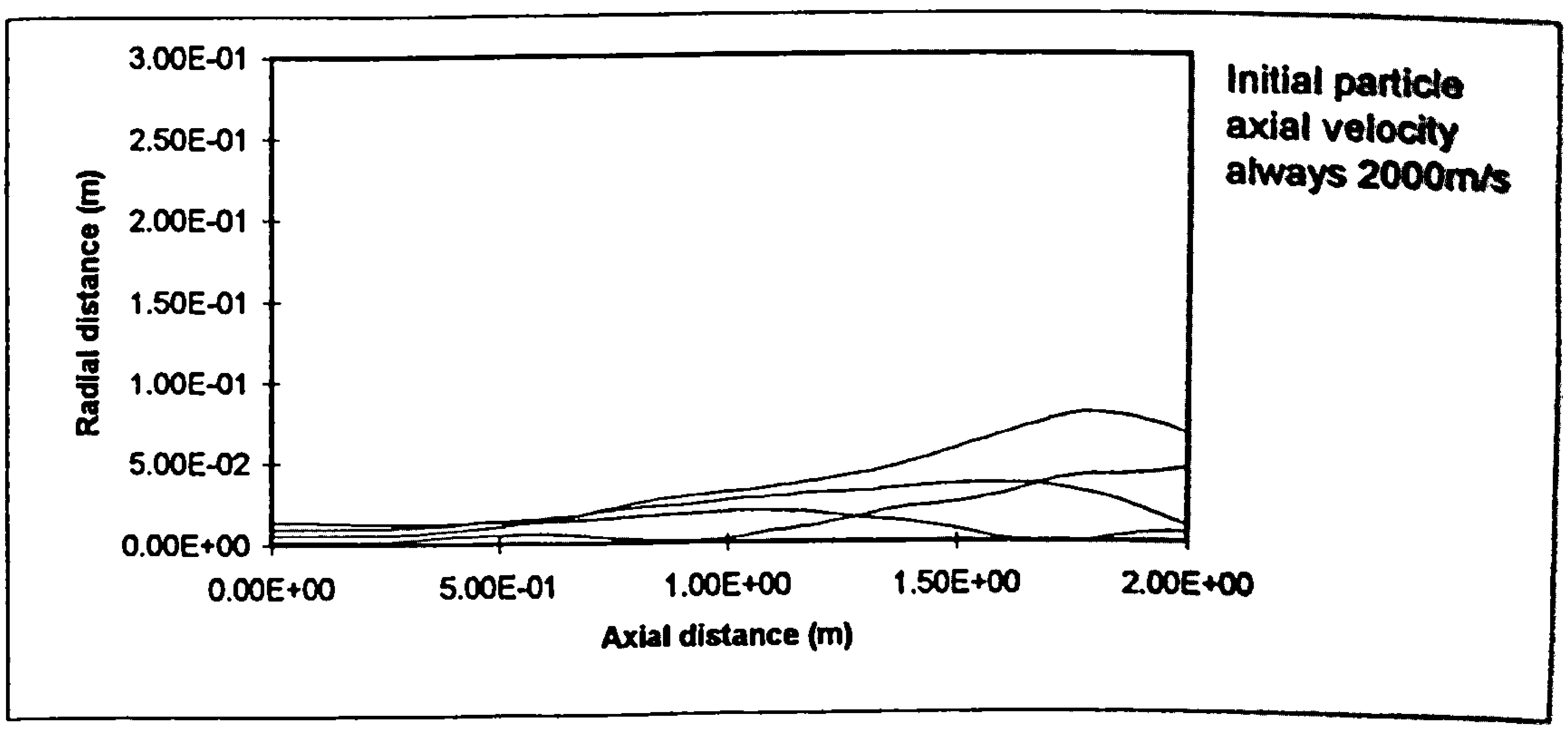


Figure 7.25 Predicted trajectories of 20 micron particles (with turbulence)

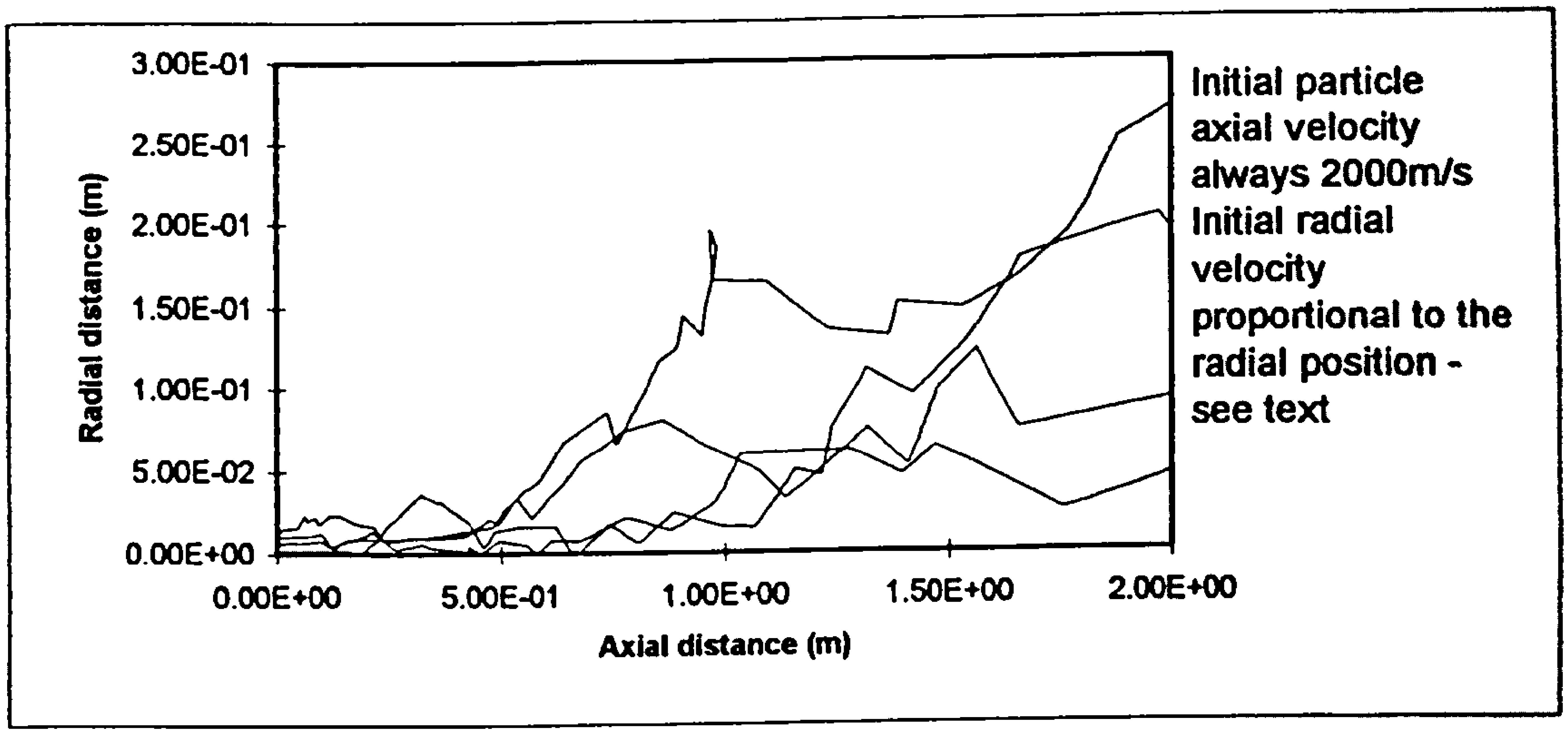


Figure 7.26 Predicted trajectories of 0.5 micron particles (with turb and rad velo)

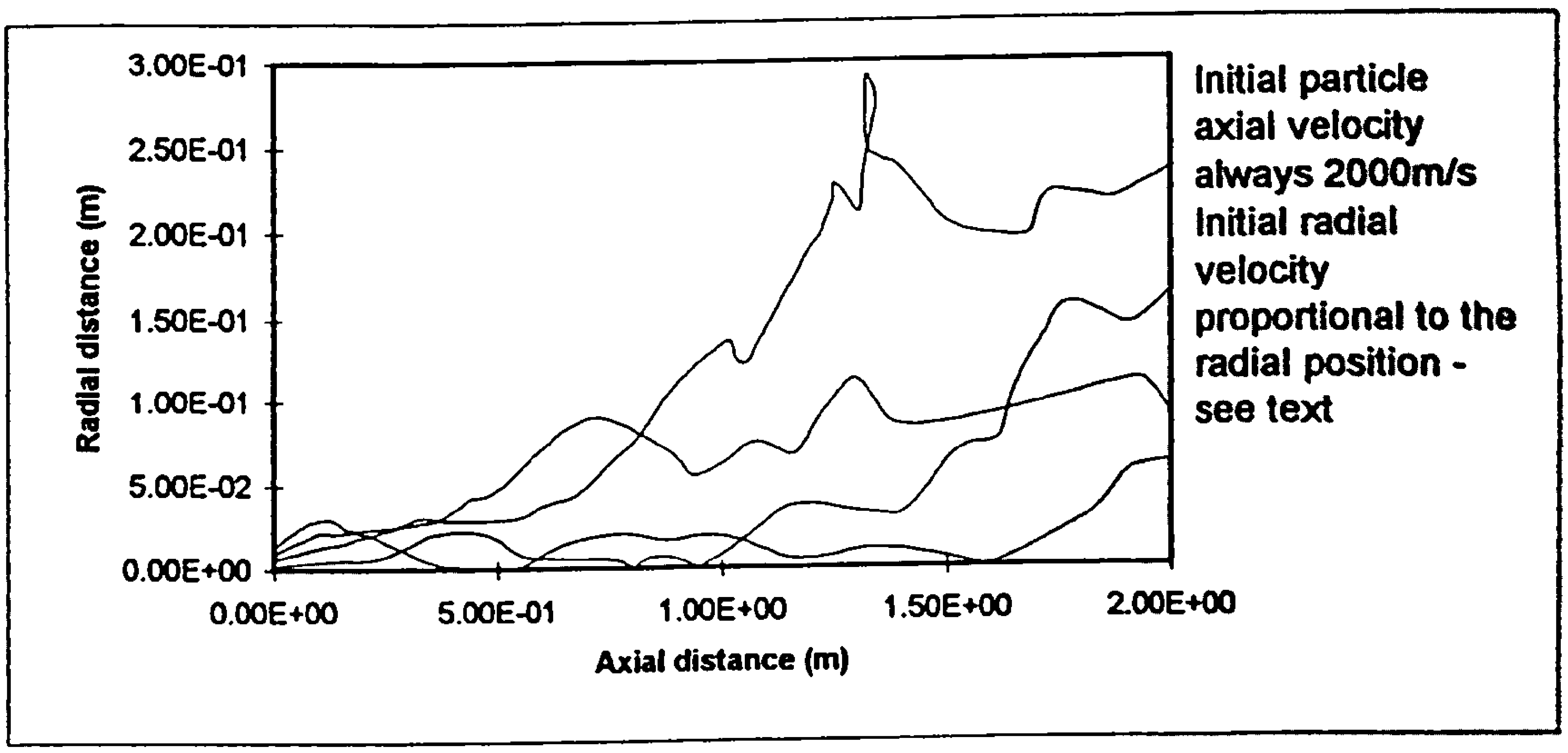


Figure 7.27 Predicted trajectories of 4.0 micron particles (with turb and rad velo)

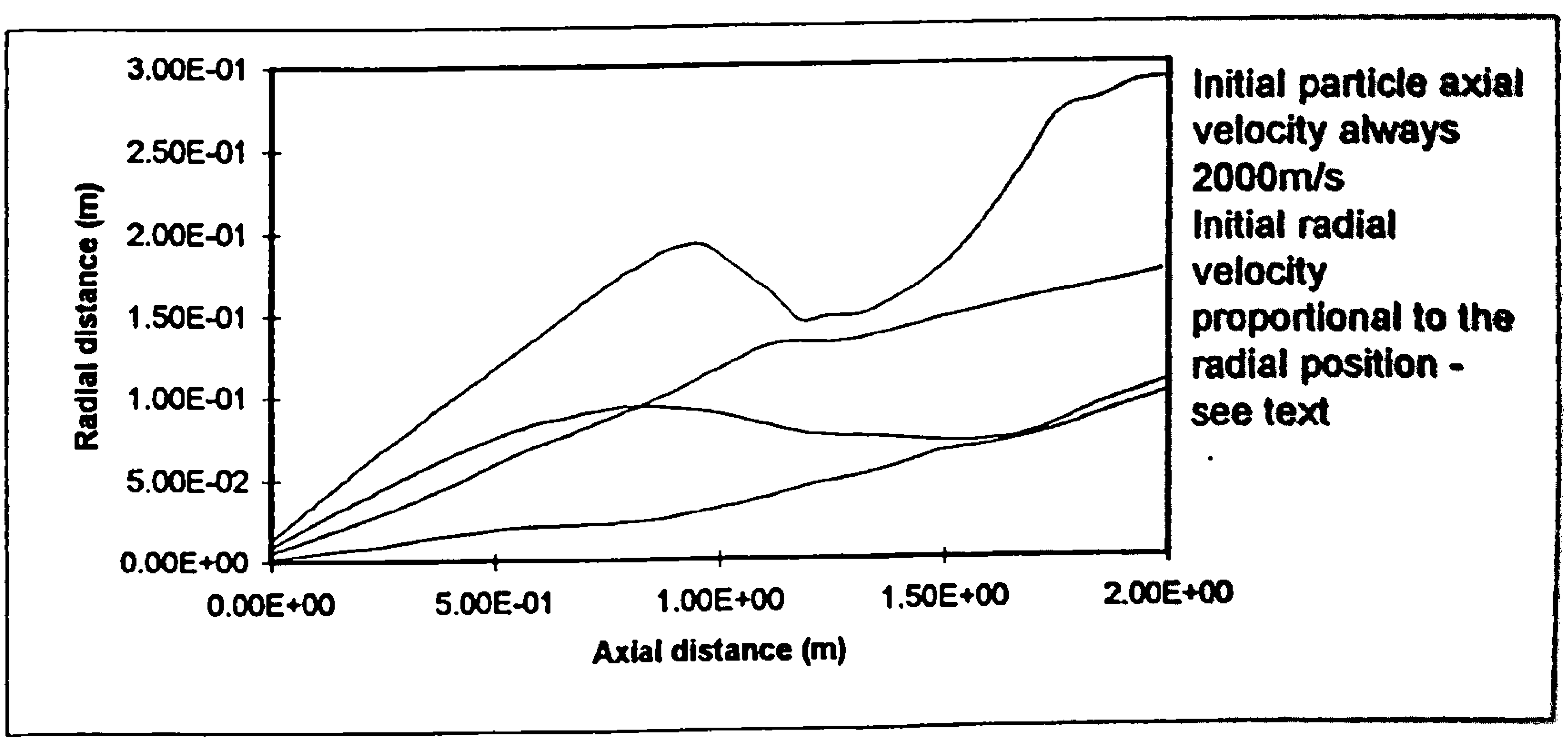


Figure 7.28 Predicted trajectories of 20 micron particles (with turb and rad velo)